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Highlights

- A classification framework for the study of maintenance policy optimization and inspection planning in wind energy industry;
- To identify models, methods and strategies used to optimize maintenance decisions and inspection procedures for various wind energy assets (turbines, foundations, cables, electrical substations, etc.);
- A systematic review of the literature over the past two decades (1997−2016);
- Identify critical observations on each category of classification;
- Suggest directions of potential interest to operational researchers.

Maintenance Optimization and Inspection Planning of Wind Energy Assets: Models, Methods and Strategies

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Abstract

Designing cost-effective inspection and maintenance programmes for wind energy farms is a complex task involving a high degree of uncertainty due to diversity of assets and their corresponding failure modes, weather-dependent transport conditions, unpredictable spare parts demand, insufficient space or poor accessibility for maintenance and repair, limited availability of resources in terms of equipment and skilled manpower, etc. In recent years, *maintenance optimization* has attracted the attention of many researchers and practitioners from various sectors of the wind energy industry, including manufacturers, component suppliers, maintenance contractors and others. In this paper, we propose a conceptual classification framework for the available literature on maintenance policy optimization and inspection planning of wind energy systems and structures (turbines, foundations, power cables and electrical substations). The developed framework addresses a wide range of theoretical and practical issues, including the models, methods, and the strategies employed to optimise maintenance decisions and inspection procedures in wind farms. The literature published to date on the subject of this article is critically reviewed and several research gaps are identified. Moreover, the available studies are systematically classified using different criteria and some research directions of potential interest to operational researchers are highlighted.

Keywords

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1. Introduction

Global warming, binding targets on greenhouse gas emissions and high costs of fossil fuels have created an urgent need to shift from traditional sources of energy to renewable ones. This shift to renewable sources of energy has accelerated at a very rapid pace after the Fukushima Daiichi nuclear disaster in Japan in March 2011 [1]. Wind power is recognized as one of the most attractive renewable energy sources which supplies an affordable, inexhaustible and clean energy to the economy. Over the last decade, wind power generation has experienced an extensive and worldwide growth. For instance, the cumulative installed capacity of wind power in the European Union (EU) has increased from 47.8 gigawatts (GW) in the year 2006 to 153.7 GW in the end of 2016, representing an annual growth of over 12% (see Figure 1). The share of wind power in EU's electricity supply was 10.4% in 2016, while it is forecasted to reach up to 20% by 2030 [2].

"Fig. (No. 1)"

Figure 1. Cumulative installed wind power capacity in the EU during 2006–2016 [2].

Along with the growth of the market for wind energy, a great deal of attention has been focused recently on minimising operation and maintenance (O&M) costs of the installed wind turbines while ensuring high levels of reliability and safety. Currently, the O&M costs (including all expenditures associated with planned and unplanned repair tasks) constitute a substantial part of the total life-cycle cost of wind turbines. According to existing statistics, the O&M costs of a wind project with twenty-year life span account for about 15–30% of the overall energy generation cost or equivalently 75–90% of the initial investment [3].

Wind farm owners and operators have been under increasing pressure recently to reduce O&M costs. It will become even more critical in the near future as the wind turbine capacity ratings continue to rise and the wind farm siting moves towards offshore locations. O&M cost reduction can mainly be achieved by developing and implementing 'cost-effective' and 'well-planned' inspection and maintenance programmes for wind farms. Nowadays, the planned maintenance tasks are undertaken during periods when demand for electricity is low (i.e., low-load seasons) or while service vessels (ships, helicopters, lifting cranes) are available to provide logistics support. It has been reported in some large wind projects (e.g. Opti-OWECS[1]) that a significant portion of annual budget is wasted as the result of unnecessary or improperly carried out maintenance activities. A cost-effective maintenance strategy aims to reduce the frequency of service interruptions as well as avoiding undesirable consequences of such interruptions. The maintenance tasks affect system reliability in a way that if too little maintenance is performed, it may result in an excessive number of costly failures and high production losses. However, if maintenance activities are performed too often, the reliability will improve but the cost of maintenance may potentially increase to unsatisfactory levels [4]. For this reason, finding "cost-optimal" solutions for inspection and maintenance operations at wind farms requires an appropriate balance between reliability targets and the cost to achieve those targets.

Maintenance optimization is defined as a method aimed at determining the most effective and efficient maintenance plan (i.e., inspection time and frequency, work preparation, required maintenance resources) so that the best possible balance between direct maintenance costs (e.g. manpower cost, logistics and transportation costs) and the consequences of not performing maintenance (e.g. loss of power production and assets) is achieved. Designing an optimal maintenance plan during the relatively long life span of wind farms is a complex task involving a high degree of uncertainty due to diversity of assets and their corresponding failure modes, existence of various dependencies among components of assets, weather-dependent transport conditions, unpredictable spare parts demand, insufficient space for replacement or poor accessibility for maintenance and repair, limited resources in terms of supply vessels, specialized equipment, trained workforce, etc. Thus, it is crucial to develop effective models and efficient techniques capable of incorporating all the factors and uncertainties associated with wind farm inspection and maintenance.

In recent years, many researchers and practitioners have shown their interest in the study of maintenance policy optimization and inspection planning for wind energy systems [5−7]. However, the literature on classification of the associated models, methods and strategies has been very limited and there remains a big gap between academic research and application in practice. In this paper, we propose a conceptual classification framework for optimizing maintenance decisions and inspection procedures in the wind energy industry. The academic studies as well as industrial applications reported on the topic are identified, reviewed and classified systematically. The relevant issues in each category are discussed in details and several gaps are identified subsequently. Some research directions of

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[1] Structural and Economic Optimization of Bottom-Mounted Offshore Wind Energy Converters

potential interest to operational researchers are also highlighted. To the best of the authors' knowledge, this paper is the first study to review a large number of research works and industrial case studies carried out over the past two decades (1997–2016) on the inspection planning and maintenance optimization of wind energy assets, including: wind turbines, support foundations, power cables and electrical substations. The findings of this research can provide valuable insights to researchers about the procedures and methodologies used for inspection and maintenance decision-making of wind energy farms.

The rest of this paper is organized as follows. First, the classification framework applied to this study is proposed; then, for each category of classification the available literature is reviewed and the relevant issues are discussed; and last, we outline our conclusions and give a brief discussion of future research topics.

2. The framework

In this section, we introduce a classification framework to identify various theoretical and practical issues including the models, methods, and the strategies employed by wind farm operators for inspection planning and maintenance optimization of wind turbine components and structures. According to the framework shown in Figure 2, the available studies on the subject can be categorized using the following criteria:

(a)   System configuration (type of wind power asset and the level of system modeling);
(b)   Decision-making attribute (planning horizon, the decision-maker and the availability of field data);
(c)   System failure modelling (type of failure and the failure modeling approach);
(d)   Optimization model (optimality criterion and the solution technique);
(e)   Maintenance strategy (maintenance policy and the repair effectiveness).

"Fig. (No. 2)"

Figure 2. The classification framework proposed for the study

The above five classification criteria are then decomposed into various categories. For the purpose of this categorization, the academic studies and industrial best practices reported to date in the literature were identified, reviewed, and analyzed. The selected studies include contributions from both scholars and practitioners in scientific journals, master's and doctoral theses, textbooks and case study reports. Conference papers and unpublished dissertations were excluded from this study because of their wide variety of contexts and the difficulties in obtaining manuscripts, particularly those dating back more than a decade. As the literature was scattered across numerous journals and government reports, the following online sources were searched by text mining techniques and the use of citation indexes:

ABI/INFORM Global – ProQuest; Academic Search Premier; Blackwell Synergy; Business Source Premier – EBSCOhost; Compendex (Engineering Village) – Elsevier Engineering Information; Emerald Fulltext; IEEE Transaction; ISI Web of Knowledge; NTIS - Ovid (SilverPlatter); Scopus – Elsevier; Springer Link; and Wiley InterScience.

For the searching criteria, two primary keywords of "wind energy" and "maintenance" were first used. Next, other search terms such as "wind turbine", "wind farm", "inspection", "model", "method", "technique", etc. were combined with the primary keywords for wider search results. Then, the full text of each work was carefully reviewed to eliminate those that were not related to the field of "optimization" or "scheduling". Finally, two hundred and forty-six publications including one hundred and seventy-nine journal articles [8–186], thirty-seven master and doctoral dissertations [187–223], twelve textbooks [224–235], and eighteen industrial reports [236–253] were selected for their relevance to the topic. Figure 3 represents a bar chart of number of publications concerning maintenance policy optimization and inspection planning of wind turbine systems in five-year periods, from 1997 to 2001, 2002 to 2006, 2007 to 2011, and 2012 to 2016.

"Fig. (No. 3)"

Figure 3. Distribution of the studies by year of publication (1997-2016).

As can be seen, over 72% of the publications have appeared during last five years which indicates the increasing importance of the maintenance optimization in wind energy industry. In following five sections, a detailed distribution of the publications classified according to the proposed framework is given. Since a large number of studies have been published in each category, only a brief description of some featured publications is provided.

3. System configuration

3.1. Type of wind power asset

A wind farm system includes different groups of *mechanical*, *electrical* and *structural* assets including wind turbines, foundations (e.g. gravity based, suction-bucket and pile), support structures (e.g. monopile, tripod and jacket), transition pieces, connection cables, electrical substations, etc. Wind turbines convert energy from the wind into electrical energy. The foundations provide support for the wind turbine structures that are installed above sea level. Support structures are used to connect the transition piece or tower to the foundation. Electrical substations connect the wind turbines to the national electricity grid. Connection cables transmit the power from the individual turbines to the substation.

In general, there are two alternatives of wind power generation, namely, *onshore* and *offshore*. The technologies involved in both the onshore and offshore wind turbines are almost similar. One of the main differences between onshore and offshore wind turbine designs is their foundation structures. Onshore wind turbines are fixed to the ground with a

concrete foundation, whereas offshore wind turbines have their foundations on the sea bed (fixed-bottom) or in the water (floating). In recent years, a large number of wind farms have been built in offshore locations due to high wind resources and the availability of large areas for installation. According to existing statistics, the O&M cost of offshore wind turbines accounts for larger portion of the cost of power generation than that of onshore wind turbines. The O&M costs for onshore wind farms comprise 5 to 10% of the cost of energy (COE) while it is estimated to be between 20 to 35% in offshore wind projects. This big difference might be due to negative impacts of offshore environment on performance of the wind turbines. Offshore wind turbines have to withstand harsh maritime conditions and their accessibility for maintenance and repair is generally poor in periods of strong wind and high waves. Moreover, the maintenance expenditures will be much higher for wind projects constructed in ultra deep waters at long distances from the shore. Therefore, in order to make offshore wind power generation more cost-competitive with onshore production as well as with the other sources of offshore renewable energy (wave and tidal), the associated O&M costs must be significantly reduced.

While building an optimal maintenance and replacement model for wind farms, the following key factors must be taken into consideration:
- size and orientation (micro-sitting) of the wind farm;
- power rating, and capacity factor of the wind turbines;
- reliability of the wind turbines;
- accessibility and availability of support vessels and transportation means;
- distance to shore and water depth; and
- meteorological surrounding conditions (wind, waves, and visibility).

A brief review of the literature shows that a lot of research has been done on optimization of the maintenance decisions for onshore wind farms (see, e.g. [23, 72, 189]). But, the existing models need to be extended to address the unique characteristics of the offshore wind farms. Utne [35] proposed a framework to make the maintenance activities more efficient for offshore wind turbines located in remote deep water areas. The two PhD dissertations of Karyotakis [203] and Sinha [223] studied the optimization of maintenance strategies for offshore wind farms. Tavner [226] in his recent book addressed the reliability, availability, and maintainability (RAM) challenges of offshore wind farms. The readers can also refer to [11, 29, 44, 53, 55, 56, 61, 70, 89, 104, 106, 111, 123, 128, 129, 133, 136, 144, 145, 146, 147, 157, 161, 163, 164, 167, 168, 171, 179, 180, 202–205, 214, 219, 222, 230, 248, 251] for further reading on optimal inspection and maintenance of the offshore wind turbines. Also, the studies [24, 60, 199, 206] and [247] are concerned with the inspection planning of foundation structures, power cables and substations, respectively.

Since the maintenance optimization process is considered as a typical complex decision-making problem, the need for software-based solutions has also greatly increased. In this line, Sinha *et al.* [90] recently developed an offshore-centric software package for optimization of the maintenance decisions in wind farms.

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3.2. Level of system modelling (component, wind turbine, wind farm)

The optimization of maintenance decisions in the wind energy sector can be done regarding a hierarchical scheme including the three levels of component, wind turbine, and wind farm (grid). These modelling levels are described as following:

- *Component level*

At the component-level analysis, an optimum maintenance decision model is developed for individual critical components of system, such as gearbox, rotor blade, and generator. In this analysis approach, each component is considered as an isolated unit and the possible dependency among components is neglected. Over the past two decades, a vast majority of the literature focuses on optimization of the maintenance for individual components (or being possibly assimilated to single-unit systems). Besnard and Bertling [30] presented an approach for optimization of the inspection interval and condition monitoring strategies for a blade whose deterioration is classified according to the severity of damages. In another work, Deng *et al.* [50] proposed a maintenance optimization model to determine the inspection interval for wind turbine gearbox such that the mean profit per unit time was maximized. Igba *et al.* [154] developed an approach for evaluating the effect of preventive maintenance (PM) interval on reliability and O&M costs of wind turbine gearbox. The readers can also refer to these references for further: [9, 10, 46, 48, 64, 68, 89, 94, 97, 107, 110, 116, 134, 152, 159, 164, 165, 174, 228, 250].

- *Wind turbine level*

Even though the single-unit maintenance models are generally considered as a basis for building more complex models, they cannot be applied to real-world systems. The component-level models assume that the components are independent, and thus are replaced individually (one-by-one). However, a single component failure in the system may affect the performance of other components which are structurally dependent, and it may cause a multiple component replacement. The related factor leading to multiple item replacements is called *common cause failure* (CCF) (for more see [198]).

It is very often observed that some critical components in wind turbine are stochastically dependent on each other. Stochastic dependence implies that failure or degradation of one component can influence the lifetime distribution of other components (e.g. construction error). Neglecting component dependencies while optimizing the maintenance and repair decisions may lead to sub-optimal or even wrong solution to the problem and thereby increased cost of maintenance and system downtime. When considering the key components, a wind turbine can be treated as a *series* reliability system. In these types of systems, the components are connected together in series and any failure in one of the components causes the failure of entire system. A repair policy for a series wind turbine system was studied in [15, 16, 21]. For more references on system-level maintenance optimization approach, the readers can refer to [20, 22, 27, 29, 31, 32, 36, 38, 53, 55, 56, 59, 62, 71, 73, 78, 80, 82, 99, 178, 113, 118, 121, 131, 132, 148, 150, 158, 161, 162, 163, 170, 182, 185, 190, 192, 197, 208, 218, 220, 221, 225].

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- *Wind farm (grid) level*

An increasing interest has been recently devoted to the development and optimization of maintenance strategies for large-scale wind farms which consist of hundreds of wind turbines. The development of maintenance optimization models for a large-scale wind farm is much more complex than that for an individual wind turbine. The maintenance decisions for a group of wind turbines in a wind farm must be made in conjunction with what happens to the other wind turbines. Generally, two kinds of dependencies are considered between wind turbines in a farm: failure dependence (or correlation) and economic dependence. Failure dependence means that once a wind turbine is shut down for maintenance, all the posterior wind turbines in farm may also have to be stopped. Economic dependence is, when a support vessel is hired to carry out the repair actions on a failed item, it might be economical to take this opportunity and perform some preventive maintenance (PM) tasks on non-failed (but soon-to-fail) wind turbines.

Failure and economic dependencies among the wind turbines have received very limited attention to date. Tian *et al.* [45] identified two types of dependencies among wind turbines in a wind farm. The first type of dependence is to share maintenance set-up costs between different wind turbines, and the second type is the dependence exists between wind turbines with high risk of failure. Pérez *et al.* [160] proposed algorithms for scheduling maintenance processes in wind farms with multiple turbines comprising multiple components, including the gearbox, power generator, blades and control system. Amayri [200] investigated the optimal condition-based maintenance policy for a wind farm consisting of various types of wind turbines with different lead times. For more references on this category, the readers can refer to [11–13, 26, 34, 37, 41, 51, 61, 65, 66, 69, 70, 72, 77, 79, 83, 86, 98, 101, 103, 106, 111, 114, 128, 129, 137–139, 144–147, 149, 153, 157, 167, 168, 172, 173, 175, 179, 184, 201, 205, 219, 239].

4. Decision-making attributes

4.1. Planning horizon (length, time-state)

The planning time horizon in maintenance optimization can be studied from two different views: the length of time horizon, and the type of time states. These aspects are described as following:

- *Length of time horizon (infinite/finite/random)*

The length of planning period for optimal maintenance decision-making problem is normally defined as either *infinite*, *finite*, or *random*. Infinite time horizon models deal with decisions that have long-lasting effect (e.g. for twenty-five years) on system O&M. This kind of models often uses the net present value (NPV) technique to recalculate all costs of maintenance to the present value (for more see [81, 136, 158, 196]). In finite-time planning models, the horizon can represent, for example, the period of a repair contract set by the manufacturer or an independent service provider (see, e.g. [155]). The random time horizon models assume that the system terminates at a random point of time, e.g. the system is

replaced by a new one either at random failures or at a given operational age, whichever comes first (see, e.g., [162, 163]).

- *Time states (discrete, continuous)*

Maintenance scheduling models, depending on the considered time state, can be divided into two classes: discrete and continuous. Discrete-time models assume that the maintenance tasks are scheduled at discrete points in time, whereas continuous-time models relax this restriction. In practice, the duration of maintenance activities and transportation times are expressed as integer multiples of time periods whose length may vary from one hour to one week. Besnard *et al.* [194] proposed an opportunistic maintenance optimization model using a discrete-time scale representation for offshore wind farms. The scheduling horizon was divided into a series of short and long time intervals, depending on the availability of forecasting information. Kovács *et al.* [41] developed an optimal wind farm maintenance schedule over a short-term rolling horizon (e.g. three to seven days). In a rolling horizon, the maintenance schedule is updated frequently to react to changes in meteorological surrounding conditions (wind, waves, and visibility). For more references on discrete-time maintenance models, see [118].

4.2. Decision-maker

The maintenance optimization problem in the wind energy industry can be considered from three competing points of view—wind turbine manufacturer, wind farm owner and operators, and the independent service providers.

- *Wind turbine manufacturer*

Nowadays, wind turbines are sold with a 2- to 5-year full-service contract from the manufacturers. Under this contractual agreement, the manufacturer is obliged to rectify any system failures caused by design, manufacturing, and quality assurance problems as well as provide technicians over a specified period of time. Offering a full-service contract for wind turbines may result in significant servicing costs to the manufacturer. This servicing cost typically involves the costs of repairing failures through corrective maintenance (CM) during the early years of operation, called 'infant mortality' [34]. Therefore, finding an effective way to reduce the servicing costs over this period has become an issue of great importance to wind turbine manufacturers.

One possible way to reduce servicing costs is to make sound decisions on design of wind turbines which is known as 'design for reliability (DFR)' in the context. The main purpose of implementing DFR techniques in the wind turbine manufacturing industry is to minimise the number of failures experienced over the lifetime, which results in enormous savings in maintenance and energy production costs. The DFR methodology has received an increasing importance in recent years, especially for some critical components like rotor blades, gearbox, and generator (see [8–10, 17, 187]). The readers can also refer to [243] as an industrial report on optimising the design processes for wind turbines in order to reduce the associated O&M costs within the RELIAWIND project.

- *Wind farm owner and operators*

The system owners' point of view on maintenance optimization might be totally different from wind turbine manufacturers'. After the expiration of service contract, the maintenance expenditures are borne completely by the wind farm owners until wind turbines reach the end of their service life. The O&M costs of a wind turbine over its operational life can be controlled through conducting preventive maintenance actions. To this aim, scheduled PM actions are carried out during the constant failure rate period (between fifth year and fifteenth year of operation) to prolong the useful lifetime as well as over the wear-out period (usually after the fifteenth year of operation) to reduce the degradation rate. Ortegon *et al.* [113] presented a system dynamics (SD) approach to model the interactions between maintenance, reliability, and technological obsolescence on the remanufacturing of a wind turbine at the end-of-use (EOU). The study suggested that regular preventive maintenance (PM) avoid/slow functional obsolescence, and as a result, the remanufacturing cost is reduced. Recently, a number of wind turbine manufacturers (see [246, 252]) launched a program to extend the twenty-year lifetimes of the 850 kW wind turbines to an expected life of thirty years or even more.

- *Independent service providers*

Currently, many of the wind farm owners employ an independent service provider to carry out the maintenance tasks under properly drafted contracts. Maintenance contracts usually specify a target for the 'availability' of wind turbines (i.e., the proportion of time that system is functional and working). Hence, the service provider—sometimes, the service department of the manufacturer—aims to maximize the availability whilst minimizing the production losses. Jin *et al.* [155] proposed a game-theoretical optimization model to minimize the O&M costs of wind turbines under a performance-based contract (PBC). According to this type of agreement, the wind farm owner defines an availability target and signs a contract with a service provider. Then, the service provider will be committed to reliable performance of the wind turbines.

4.3. Availability of field data

The data availability is seen as the biggest challenge in RAM studies of the wind energy industry [39, 242, 250]. Effective management of maintenance activities in a wind farm requires a database of *failure data* to model the system failures as well as some *supplementary data* to evaluate the different maintenance strategies. Failure data (e.g. times to failure) are collected and stored during the operation as well as servicing of the wind turbines. They can usually be collected from Supervisory Control And Data Acquisition (SCADA) or some other sources like WMEP in Germany (www.wmep.org), WindStats in Denmark (www.windustry.org/resources/wind-stats-newsletter), VTT in Finland (http://www.vtt.fi), or Elforsk in Sweden (http://www.elforsk.se). The failure databases usually contain valuable information about the performance and failure history of wind turbines which can be effectively utilized to detect the potential future failures. Supplementary data (e.g. cost parameters, production levels) are collected from other internal or external sources.

Currently, much of the data available in wind farm databases suffers from inaccuracy, inconsistency, and incompleteness. However, a brief review of the literature shows that very few research has been conducted on the optimization of maintenance decisions under data limitations. Coolen *et al.* [22] applied non-homogeneous Poisson process (NHPP) models, in particular the power law process, to derive the reliability of wind turbines and some critical subsystems from grouped data with little information on individual turbines or maintenance activities. Guo *et al.* [28] proposed a three-parameter Weibull failure rate function for wind turbines when the field failure data is incomplete. Nguyen *et al.* [84] and Nguyen [217] presented a data integration framework for optimization of the O&M decisions within offshore wind farms.

5. System failure modelling

5.1. Type of failure (minor, major)

It is important to distinguish between the different types of failures that may occur in a wind farm because the required resources to perform the associated repair tasks will be different. Basically, the wind turbine failures can be classified into two types of *minor* and *major* (catastrophic) [164]. Minor failures (e.g. microscopic cracks) are often detected remotely and are rectified through a minor inspection, whereas major failures (e.g. a metre-long fracture) can only be removed by a major repair or replacement. The resources required to carry out maintenance tasks will vary according to whether the action is a major overhaul or just a minor repair. For instance, a minor repair task on the yaw brake pads can be executed by a team of two technicians and it normally takes about 30 minutes. In contrast, a major repair task on a rotor blade (e.g. de-icing) needs two teams of two technicians and it takes almost four hours. Moreover, in order to conduct a minor inspection the maintenance crew can be transported by either a workboat or a helicopter, while for a major repair they must be sent only by a workboat.

5.2. Failure model

The method used for modelling of the failure process of components is a very important input for the maintenance optimization analysts. These methods can be classified into different types as follows:

- *Black–box /Grey–box/White–box*

In the black–box modeling approach, a wind turbine system is considered as a single module and its reliability is estimated using the available failure data (e.g. the recorded times-to-failure). Since this model does not consider the relationships between components, it is often used for optimization of the maintenance decisions at component level. In the grey–box modeling approach, the degradation process underlying a failure is modeled. This implies that the deterioration can be observed (classified or measured) directly or indirectly by relevant deterioration indicators. Besnard [210] used a grey–box approach for deterioration and maintenance modeling of wind turbines. The approach consists of a life cycle cost (LCC) model for the whole lifetime of wind turbines which takes into account

the cost consequences of random failures (e.g. lightning strike). In the white–box modeling approach, the system is considered as a collection of components, subsystems and assemblies arranged together in a specific structure to achieve the desired functionality. Thus, the technique can be useful in deriving the reliability of a system based on the reliability of its constituent components using classical reliability theory. Andrawus *et al.* [15] applied the white–box approach to assess the failure characteristics of a horizontal axis wind turbine system. An optimal maintenance strategy was also proposed to minimize the total LCC of wind farm.

- *Delay-time model*

The concept of delay-time model is very similar to the Potential-to-Functional Failure (P-F) curve in reliability-centred maintenance (RCM). The P-F curve illustrates the point where a failure starts occurring but not detectable (P), and the point where the system fails (i.e., the functional failure point) (F). The time taken from potential failure to decay into functional failure is called 'P-F interval'. In delay-time models, the criterion for declaring points P and F is very important. In the RCM analysis, the point P is determined on the basis of experts' judgments. When the experts agree that a potential failure is present, the maintenance technicians immediately decides on replacing the component. If this is not the case, then the periodic inspections have to be conducted at intervals of length *x* aiming to estimate the severity level of failures (*x* is shorter than the average PF interval). The delay-time model has been well addressed in reliability analysis of wind turbine systems (see [16]). This model can be used for deriving the reliability of wind turbine structural components by the means of structural reliability theory, limit state modeling, first-order reliability method (FORM) or second-order reliability method (SORM). In a study carried out by Andrawus *et al.* [21], a delay time maintenance model was proposed to determine an optimum inspection interval for major components of wind turbines.

- *Multi-state model*

Most of the existing failure models assume that a system consists of binary-state components whose behavior is described only by two possible states: perfect functionality and complete failure. However, many real-world systems are composed of multi-state components having different performance levels and several failure modes with various effects on the entire system's performance. Such systems are called multi-state systems. Multi-state reliability methods are found to be very useful for modelling the failures and repair activities of wind turbines as they can include the dynamic characteristics of the system. For instance, since wind speed does not maintain a specified stable level, using a multi-state model would result in a more accurate estimation of the system's reliability.

- *Degradation model*

Many of the wind turbine components such as gearbox and generator or wind farm structures such as foundations are exposed to degradation processes such as fatigue cracking, corrosion, corrosion fatigue, scour, etc. Wind asset degradation is a very complex process as it depends on numerous physical and environmental factors (such as material,

stress loads, temperature) and usually manifests itself in different forms of wear, fatigue, and crack generation. The prediction of degradation level (e.g. crack size) is very important for reliability analysis as well as scheduling of inspection and maintenance tasks for wind turbines. The degradation behavior of a component is usually modeled by a stochastic process, namely $\{X(t), t \geq 0: X(0) = 0\}$ which represents the level of deterioration (e.g. accumulated wear) at time t. If no maintenance action is taken, $X(t)$ will be continuous-time and monotonically increasing function.

The degradation process of wind turbines has been extensively analyzed in the last decade and some models have been developed to assess the risks associated with degradation failures (for more see [227]). Among the stochastic processes considered in this context, the *gamma* process has been satisfactorily fitted to data of different degradation phenomena in wind turbines. Shafiee and Finkelstein [162] applied the gamma process to degradation analysis and maintenance planning of a group of wind turbine bearings. Le and Andrews [170] presented a reliability assessment model for offshore wind turbines subject to degradation in order to plan inspection and maintenance processes. The model captured the stochastic nature of the dynamic processes through the use of appropriate statistical distributions.

- *Shock models*

It is widely reported that the wind turbine failures are not solely caused by components' degradation. Besides degradation failures, wind turbines may also be subject to external (environmental) shocks such as destructive waves and icing damages. According to IEC 61400-3 (www.iec.ch), the external conditions of a wind farm (e.g. wind speed, wind direction, turbulence intensity) should be continually monitored and the essential design requirements must be specified to ensure the engineering integrity of wind turbines. The existing shock models are concerned with a multi-unit wind turbine system whose components are subject to different external shocks at random times and are damaged by a shock impact. In the literature, there are four groups of shock models: (i) *extreme shock models* in which a failure occurs when the magnitude of a shock exceeds a pre-specified threshold, (ii) *cumulative shock models* in which a failure occurs when the cumulative damage from shocks exceeds a critical value, (iii) *run shock models* in which a failure occurs when there is a run of k shocks exceeding a critical magnitude, and (iv) *δ-shock models* in which a failure occurs when the time lag between two successive shocks is shorter than a threshold $δ$. The readers can refer to these references for further: [164, 186].

6. Optimization framework

6.1. Optimality criterion

The objectives taken into account in the literature for optimization of the maintenance decisions are divided into the following three general categories:

- *Minimum cost*

The criterion of *minimum 'long-run average cost'* is widely used in the maintenance optimization area. Let $D(t)$ denote the expected cost of operating a system over the time interval $(0,t)$. Let L_i be the length of the ith replacement cycle and OC_i be the operational cost over the cycle. A replacement cycle is defined as a time interval between two consecutive replacements. Then, from the *renewal reward theorem*, the long-run average cost is equal to the expected operational cost over a cycle divided by the expected length of the cycle, i.e.,

$$\text{Long-run average cost} = \frac{\text{Expected cost incured in a replacement cycle}}{\text{Expected length of a replacement cycle}} = \lim_{t\to\infty} \frac{D(t)}{t} = \frac{E[OC_i]}{E[L_i]}. \tag{1}$$

For each replacement cycle, five cost drivers are often considered in model formulation, namely, *replacement cost* (of a failed item by a new one); *logistics costs* (of equipping the maintenance crew, hiring the service vessels, and ordering the spare parts); *transportation cost* (for sending the maintenance crew to wind farm); *manpower cost* (for the inspections and CM tasks on failed components); and *production loss cost* (due to wind farm breakdown). All the above costs are included in *life support cost* (LSC) which usually accounts for a significant part of the wind turbine lifecycle cost and should be minimized. To this aim, various routine inspections are carried out to improve the operating conditions of wind turbines as well as reducing cost of energy produced by wind farms. The cost of energy (COE) produced from wind farms is given by [254]:

$$COE = \frac{IC \times FCR + AOM}{AEP}, \tag{2}$$

where IC (£) is the initial capital cost of the wind farm; FCR (%/year) is the fixed charge rate; AOM (£/year) is the annual O&M cost; and AEP (kWh/year) is the annual energy production. For further reading on maintenance optimization models with minimum cost criterion, the readers can refer to [32, 44, 45, 51, 55, 68-70, 81, 103, 162–164, 185, 194, 197, 200, 208, 210, 225, 238].

- *Minimum production loss (maximum power output)*

There are several categories of energy production losses in a wind power plant, including wake losses, availability losses, turbine performance losses, electrical losses, environmental losses, etc. Wake losses are one of the most important factors leading not only to reduction of power output, but also an increase of structural loading on wind turbines. The wake losses are often caused by the momentum deficit and increased level of turbulence created by wind turbines in the wind farm. To date, the effects of energy production losses due to wake effects have been seldom considered for the scheduling of wind farm maintenance (e.g. see [97]). Availability losses are another type of production loss in wind farms. When an unexpected failure occurs in a wind turbine, the whole system stops operating until the required repair is completed. An unexpected failure results in considerable production losses in wind farms. Besides random failures, power loss may be caused by scheduled PM tasks where the wind turbines are normally shut down during the

maintenance actions. The optimization of maintenance strategies with the aim of minimizing total production losses (or maximizing total power output) has been of considerable interest to wind farm operators. Kovács *et al.* [41] developed a mixed-integer programming model to optimize the maintenance schedule of an onshore wind farm. In the proposed model, the objective function includes both production losses due to random failures and PM actions, that is,

$$\min \ \sum_{j=1}^{J}\sum_{t=1}^{T} z_{j,t} + \sum_{i=1}^{N} \delta_i y_i \,, \qquad (3)$$

where $z_{j,t}$ (≥ 0) denotes the production loss of turbine j over period t; the indices J and T represent respectively, the number of wind turbines in wind farm and the number of time periods in planning horizon. The binary variable y_i indicates whether PM task i (among N tasks) is postponed or not. This means that it may be worth postponing PM tasks, e.g. from a period with high winds to a later period with low winds, even if all resources are available. If the PM task is performed exactly after the failure, then $y_i = 0$; otherwise if it is postponed, $y_i = 1$ and a penalty cost δ_i (≥ 0) incurs to the decision-maker. The readers can refer to [12, 57, 95, 181] for further.

- *Maximum availability/reliability*

The analysis of failure data collected from various databases shows that the availability of existing wind farms is less than the target levels [95–99]% (for more see [18, 19, 42]). Generally, the following ways can be considered to achieve a higher level of availability in wind farms:
▪ Using faster transportation means;
▪ Coordinating the spare parts supply and distribution;
▪ Shortening lead times for ordering the spare parts and hiring support vessels; and
▪ Improving the reliability of wind turbines.

In order to improve the reliability level of wind turbines, a *redundant* structure for some critical components has been suggested in the literature (e.g., see [141]). Recently, wind turbine assembly manufacturers (such as SIEMENS, REpower, and Gamesa) have proposed a prototype design of six parallel-connected converter system to use in the harsh offshore environments. The benefits of applying this prototype design (i.e. improving the reliability, efficiency, and power output) have been discussed in [165]. The readers can also refer to [20, 43, 50, 59, 86, 87, 132, 148, 151, 173, 186, 209, 216, 221] for further studies on reliability/availability analysis of wind farms.

6.2. Solution technique

When the objectives are set and all necessary information is available, an optimization technique must be used to find out the optimal solution. In a broad classification, the maintenance optimization solution techniques are categorized into two types of *qualitative* and *quantitative* [190]. The qualitative techniques are subjective or judgmental and are based on estimates and opinions, while the quantitative techniques incorporate various mathematical models and statistical analysis. In this section, a generic list of all possible

maintenance optimization solution techniques is developed, taking into account the techniques found in literature and adding the ones are missing.

- *Operations research models (IP, MIP, NLP, DP)*

Integer programming (IP) assumes that the decision variables take only integer values. Problem contexts that involve both integer and continuous decision variables are termed mixed-integer programming (MIP). Non-linear programming (NLP) is the method of solving problems involving a nonlinear objective function subject to linear or nonlinear constraints. Dynamic programming (DP) is a method for solving multi-stage decision problems by breaking them down into simpler sub-problems. Nilsson [195] proposed an MIP model to optimize the maintenance management of wind farms based on a linear cost function including the maintenance expenses and production losses. For further studies on operations research models, see [41, 47, 50, 55, 69, 71, 77, 100, 168, 197, 200].

- *Stochastic models*

The O&M optimization of wind turbines greatly depends on some stochastic factors such as wind speed and wave height. A stochastic model has the capability to incorporate key random factors to predict the system condition. Veldkamp [25] proposed a stochastic model to identify the important parameters affecting fatigue loads in wind turbines. Then, a cost minimization model was presented to determine the optimal failure probabilities and partial factors in the system. Recently, various stochastic models have been proposed to determine the optimal maintenance policy for wind turbines. The readers can refer to these references for further: [72, 81, 120, 127, 153, 158].

- *Markov models (discrete/continuous Markov model, semi Markov, hidden Markov)*

Markov model is a stochastic process with the property of being memoryless. In other words, a Markov model is a sequence of realized states that the transition probability to a state only depends on the current state and not on the history of states. Markov models are widely used for modeling the deterioration of a system with several degradation states, e.g. five states including 'good (0)', 'minor degradation (1)', 'advanced degradation (2)', 'major degradation (3)' and 'failure (4)'. At each state, the next time for inspection is updated based on the maintenance decisions for the current state. If a minimal repair is performed, the system will stay in "as-bad-as-old" condition, while an imperfect maintenance leads the system to a less degradation state. At the event of a failure (state '4'), the system has to be replaced by a new one.

The deterioration process in wind turbine components can be modeled using a discrete or continuous Markov model. In discrete models, the component is observed at discrete time points, while in continuous models there is continuous observation. Byon and Ding [31] formulated an optimal maintenance model for multi-state deteriorating wind turbines using a partially observed Markov decision process with heterogeneous parameters. Ossai *et al.* [182] developed a six state Markov model to evaluate the impacts of wind turbine components maintenance on downtime and failure risks. The transition and maintenance rates at different lifecycle phases were determined using a calibrated survivability index.

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Abeygunawardane [209] in his PhD thesis proposed a Markov model for condition monitoring of wind turbine systems. In this study, a two-state model was presented for binary-state components (with two 'up' and 'down' states) and a three-state model was developed to include an intermediate state at which faults are detected.

In semi-Markov models, the transition rates to other states may change over the duration of a state and therefore, the inter-arrival times between subsequent states are not exponentially distributed. Su and Zhou [62] proposed a condition-based maintenance optimization model based on a semi Markov decision process in order to minimise the long-term *discounted* maintenance costs.

Hidden Markov model (HMM) is also being used to monitor the online SCADA data for fault detection purposes, especially when there is a lack of field failure data. The main feature of HMM is that, in a regular Markov model the states are directly visible to the observer but in an HMM only the sensor output is visible and the states are not directly visible.

For more references on Markov models, see [5, 32, 49, 70, 82, 133, 210, 212].

- *Petri net model*

Petri net (PN) model is a graphical and mathematical tool which was originally developed for the modeling and analysis of distributed systems with concurrency and resource sharing. As a graphical modeling tool, PN is composed of a set of *places* (P), a set of *transitions* (T), and a set of *directed arcs* (A). The places represent conditions and are drawn as circles, the transitions represent events and are drawn as bars, and the arcs connect transitions to places and places to transitions. In the wind energy industry, PN model has been mainly applied to fault diagnosis and reliability evaluation of wind turbines. Yang *et al.* [46] proposed a novel PN model and reliability evaluation method for the hydraulic variable pitch system of a wind turbine. The proposed PN model not only described the structure, function and operation of the hydraulic pitch system with a graphic language, but also it could clearly express the logical relations among faults. Leigh and Dunnett [178] applied the PN approach to optimise maintenance processes of a wind turbine with three types of maintenance actions, namely periodic, conditional and corrective as well as the weather condition in order to determine the accessibility of the turbine. For further references on PN models, see [128, 161].

- *Analytical models*

Analytical model is a mathematical tool with a closed form solution, i.e., the solution to the equations describing any changes in the system is expressed as a mathematical analytic function. Feuchtwang and Infield [53] developed a closed form probabilistic model for estimating the expected delays caused by sea state during the maintenance process of offshore wind turbines. They applied the model to explore the impact of different parameters such as components' reliability, time to repair, and access constraints on two specific offshore sites. In another work, Mensah and Dueñas-Osorio [59] proposed an analytic model to evaluate the wind turbine system reliability as well as failure consequences.

- *Simulation models*

Simulation model is one of the most flexible quantitative techniques that can be used for analyzing the reliability of complex systems. A simulation model has the capability to take into account all uncertainties exist in the field of wind farm O&M as well as explore the feasibility of novel maintenance strategies. The principle of a simulation model is to generate various maintenance scenarios according to the stochastic variables of model and then to evaluate the quantities of interest (e.g. cost, availability, breakdowns) for each scenario. Byon *et al.* [37] developed a discrete-event system specification (DEVS) model for simulation of the wind farm O&M. The authors implemented the simulation model under two main maintenance strategies, namely scheduled maintenance and condition-based maintenance. The results showed that the condition-based maintenance policy enables operators to reduce the failure rate of wind turbines and increase the availability of wind farm. Benmessaoud *et al.* [69] used a simulation model to optimize the schedule and the type of maintenance actions applied to a wind farm. Their model was based on a cost minimization criterion aiming to determine the optimal maintenance strategy such that a greater availability and an increased power output were achieved in wind farm. Santos *et al.* [161] used a stochastic PN model coupled with Monte Carlo simulation (MCS) for modelling and optimization of an operation and maintenance strategy based on corrective maintenance replacements and imperfect age-based preventive maintenance repairs.

For more references on simulation models, see [82, 108, 146, 149, 160, 192].

- *Bayesian networks*

Bayesian network (BN) is a probabilistic graphical model representing the conditional dependencies between failure root causes and symptoms, i.e. given symptoms, the model is able to estimate the probabilities of the presence of various faults. BN model is recognized as an efficient tool for fault diagnosis and maintenance optimization of the wind turbines. Nielsen and Sørensen [44, 112] applied the BN model to optimize the risk-based maintenance decisions of offshore wind farms such that the cost of PM effort was balanced against the costs of corrective maintenance actions. For more references on BN model, see [24, 29, 60, 214].

- *Fuzzy models*

Fuzzy models are often used when the system dynamics are not precisely known, and the information is mainly based on experts' knowledge and expertise. Dinmohammadi and Shafiee [74] developed a fuzzy-FMEA failure mode and effects analysis (FMEA) approach for risk and failure mode analysis of offshore wind turbine systems. The information obtained from the experts was expressed using fuzzy linguistics terms and a grey theory analysis was proposed to incorporate the relative importance of the risk factors. Schlechtingen *et al.* [88] proposed a condition monitoring system for wind turbines using adaptive neuro-fuzzy interference systems (ANFIS). Cross and Ma [143] proposed a fuzzy logic-based inference system for condition monitoring and fault diagnosis of wind turbines.

- *Data mining techniques*

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The SCADA system usually dumps large amounts of data from different sources being updated periodically. Very often, it is observed that the data collected from sensors is not all relevant or meaningful. In this case, data mining (DM) techniques can help wind farm operators to extract meaningful data and build models to find out how the changes in one or set of variables may affect the system performance. Thus, DM techniques can act as a key enabler in the design of a condition monitoring system for wind turbines. Kusiak and Verma [58] conducted a comparative analysis of various data-mining algorithms using the data collected at a large wind farm consisting seventeen wind turbines. Recently, in two PhD dissertations, Verma [207] and Zhang [208] used the data-mining techniques to monitor and optimize the performance of wind turbine systems based on the collected operational data and the fault logs from SCADA system. Depending upon the nature of wind turbine faults, the O&M decisions were optimized. To read further on the applications of DM techniques in wind turbine O&M, see [42, 64].

- *Intelligent-based models*

The dynamic nature of the environments in which wind turbines operate has led to the development of intelligent-based (IB) models. IB models play an important role in prediction of the system's residual life and currently are one of the key success factors in the implementation of condition monitoring systems for wind farms. IB models generally involve the development of powerful reasoning algorithms and prediction techniques such as machine learning (ML), Neural Network (NN), Artificial Intelligence (AI), and Expert Systems (ESs). Brandão *et al.* [48] introduced some applications of NNs to analyse the wind turbine condition and identify possible future failures. Zhao *et al.* [66] proposed an intelligent agent control approach to optimize the fatigue distribution of wind turbines in a large-scale offshore wind farm.

To read more on the applications of IB models in wind turbine O&M, see [56, 78, 88, 108, 122, 130, 183, 225].

- *Multiple-objective models*

Even though single-objective maintenance optimization is attractive from the modeling point of view, it does not capture all important aspects of the wind energy industry. For example, maximizing the availability of a wind farm may not imply minimizing the O&M costs. Sometimes when system reliability is maximized, the maintenance costs are still so high that they are not acceptable in practice. Multi-objective maintenance optimization is an underexplored area in wind energy. Jin *et al.* [81] proposed a multiple-objective optimization model to determine the equipment sizing, siting, and maintenance schedules of a wind-based distributed generation system such that the system cost was minimized and its reliability was maximized. Abdollahzadeh *et al.* [172] proposed a multi-objective based model to optimize the maintenance processes of a wind farm involved several different types of wind turbines. The proposed model attempts to maximize the expected rate of energy and minimize the total expected costs related to maintenance efforts.

For more references in this area, the readers can refer to [85, 114, 156, 173, 191].

A detailed distribution of the journal papers by operations research techniques used to find out the optimal solution is shown in Table 1.

"Table (No. 1)"

Table 1– Distribution of the journal papers by solution technique and maintenance strategy considered for optimization.

7. Maintenance strategy

A maintenance strategy includes a set of policies and actions that are used to "retain" or "restore" an equipment as well as the decision support system in which maintenance activities are planned. This section aims to review the O&M strategies which are employed by wind farm operators and find out the possible gaps between current practices and benchmark goals. A detailed distribution of the journal papers by maintenance strategy is shown in Table 1.

7.1. Maintenance policies

One important research area in maintenance optimization is the study of various maintenance policies used to improve system availability. There are many possible ways to classify the current practices of maintenance in wind energy. In the reference [52], the authors studied the existing maintenance strategies in wind farms and then discussed the major challenges (e.g. site and seasonal asset disturbances, dependability and asset deterioration, diagnostic and prognostic) for an effective management of O&M. From *classical* point of view, maintenance policies for wind farms can be categorized into two major classes: failure-based (reactive response) and proactive maintenance. The former is carried out when a failure occurs in one of the components and the wind turbine shuts down. But, the latter is to either repair or replace the critical components according to a prescribed criterion (e.g. at pre-determined time intervals) in order to control the rate of degradation. From *lifecycle* point of view (i.e. from the design stage to end-of-life), EI-Thalji [198] divided the wind farm maintenance policies into six categories: design and development, production and construction, diagnostic, autonomous, proactive, and prognostics (predictive) maintenance.

In a broader classification, in this paper we categorize the maintenance policies applied to wind power systems into the following groups:

- *Overhauling*

Under this policy, a major overhaul (including re-design and/or replacement of critical equipment) is carried out after a long period of time (e.g. five years). Even though overhauling may be a possible solution for highly reliable wind turbines, it cannot be considered as a long-term approach for maintaining the wind farms with high rate of failure. Bell [237] reports that a wind turbine overhaul costs almost 20% of the initial investment. Moreover, it requires some special service vessels (e.g. heavy lift cranes) which makes the process technically unfeasible.

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- *Corrective (breakdown or reactive response) maintenance*

Under this policy, a repair action is carried out after a wind turbine failure or upon a severe decline in power production. The corrective maintenance (CM) policy may be practical for small onshore wind farms with a few number of wind turbines, or for those offshore wind turbines located close to the shore in shallow waters. However, when considering future wind farms which are likely to be built in remote areas, this policy cannot be cost-effective [11]. In Opti-OWECS project, Kühn *et al.* [8, 236] showed that unplanned repair and maintenance of the failed wind turbines account for a significant portion of the annual O&M costs. Kooijman *et al*. [14] studied the current state of maintenance for offshore wind turbines in the North Sea. The authors suggest that utilizing an optimum PM policy can potentially minimize the maintenance expenditures.

- *Routine inspections*

Most of the wind farms undergo a daily routine inspection during the operation, and afterwards, one major inspection every two to three weeks. Some defects such as leakage and corrosion can be detected through *visual* inspections. However, detection of many of faults like surface cracks on the blades, electric short circuits in generator, and overheating of the gearbox require using more sophisticated inspection methods such as non-destructive testing (NDT). NDT techniques such as acoustic emission, ultrasonic, radiography, thermographic, electromagnetic, and eddy current can provide quantitative information about the deteriorated condition of wind turbine components and structures.

- *Performance based PM (calendar or time based, age based, use based)*

This broad group of maintenance policies is described as the repair activities undertaken at specified dates (i.e., *calendar* or *time based*), or after a fix period of time depending on the age of components (i.e., *age-based*), or according to the total amount of electricity produced (i.e., *operational-based*) in order to reduce the likelihood of failure or the degradation rate of system. Karyotakis [203] identified two types of calendar based maintenance which are commonly applied to offshore wind farms: PM1 with one scheduled visit per operational year (typically during July), and PM2 with two scheduled visits (often during May and October). As an example, Horns Rev (also known as Horns Reef) offshore wind farm in the east coast of the North Sea undergoes PM2 program (http://www.dongenergy.com). First, a minor PM task is carried out during January and then a major PM is performed during the summer. The minor PM task usually takes two days and it costs about 1000€ for each wind turbine, whereas the major PM takes three days and it costs roughly around 1500€ per wind turbine. A main issue encountered in the age- or operational-based maintenance policies is to find out an optimum time interval or operation level for preventive replacement of critical assets so that system availability/reliability is maximized under given constraints. Su and Zhou [63] presented an optimum age-replacement maintenance policy for a wind turbine system with taking into account the economic dependence among components. A cost minimization model (including all costs related to repair, maintenance, replacement, and system breakdown)

was developed and a branch and bound algorithm was utilized to find out the optimal solution. The readers can refer to these references for further: [21, 50, 154].

- *Failure-limit policy*

Failure-limit maintenance policy for wind farms is classified into various types. The most commonly used one is a *number-dependent* policy in which the maintenance decisions are made based on the number of system failures. For instance, the maintenance crew is sent to wind farm to carry out repairs or replacements when the number of failed wind turbines reaches a pre-specified number m, where $m = 1, 2, …, N$, and N denotes the total number of wind turbines in wind farm (for more see [89, 197]). The failure-limit maintenance policy can also be based on *cost* or *failure likelihood* criterion, i.e., a component undergoes PM action if the associated cost [failure likelihood] is less than a predetermined threshold; otherwise it is replaced by a new one [45].

- *Reliability-centered, condition based, and predictive maintenance*

Reliability centered maintenance (RCM) has been widely recognized and implemented in the wind energy industry [27, 115, 166, 229, 245]. RCM is used to optimize the maintenance decisions of a system while preventing its reliability level from dropping below a certain specified value. It involves maintaining the system functions, identifying the failure modes, prioritizing the potential risks, identifying PM requirements, and selecting the most appropriate maintenance tasks. RCM is usually applied to critical components/subsystems whose failures could result in catastrophic system failure or high loss of power production. To this aim, many different tools including the failure mode and effects analysis (FMEA), failure mode, effects and criticality analysis (FMECA), and fault tree analysis (FTA) are utilized (e.g., see [74, 204]). Fischer *et al.* [54] applied the RCM methodology to two types of Vestas wind turbines: V44-600kW and V90-2MW. A criticality analysis on the basis of failure frequency and incurred consequences was done for four critical subsystems, namely gearbox, generator, electrical system, and hydraulic system.

Condition based maintenance (CBM) is now the most extensively used policy in the wind energy industry and its related literature is vast. CBM employs continuous monitoring and inspection techniques to detect incipient faults early in their evolution and to determine any necessary maintenance tasks. On the other hand, CBM works on the current condition of each component and before it drops below a certain threshold, a preventive repair or replacement action is carried out.

The benefits of using CBM for wind turbines have been studied in some publications. Nilsson and Bertling [19] quantified the benefits of implementing CBM in onshore and offshore wind energy sectors using an LCC analysis. McMillan and Ault [18, 23] and McMillan [192] used the simulation techniques to evaluate the cost effectiveness of CBM in onshore wind farms. Wiggelinkhuizen *et al.* [26] evaluated the added value of applying CBM policy to offshore wind farms within a European project called CONMOW (CONdition Monitoring for Offshore Wind farms). Van Horenbeek *et al.* [94] proposed a stochastic simulation model to quantify the economic added value of applying an imperfect

CBM policy to wind turbines. A case study on a wind turbine gearbox was used to illustrate the approach. Haddad *et al.* [103] proposed a model to evaluate the individualized maintenance policies for different system instances and then quantified the value of CBM at all points in time from prognostic indication to the end of the remaining useful life (RUL). The readers can also refer to [36, 62, 193] for further reading on CBM of wind turbines.

Predictive maintenance (PdM) includes 'the use of modern measurement and signal processing methods to accurately predict and diagnose system condition during operation'. PdM is often referred to as CBM in the wind energy industry, however, PdM uses current and prognostic information of components to optimally schedule maintenance actions, while CBM only uses current component state information. Recently, many articles have addressed the optimization of PdM decisions for wind farms. For some references on PdM optimization, the readers can refer to [42, 93, 215, 225].

- *Risk based maintenance*

Risk based maintenance (RBM) aims to reduce the overall risks associated with unexpected failures of wind turbines. The inspection and maintenance schedule is optimized on the basis of quantified risks caused by failure of components. The high-risk components (e.g. rotor blades, gearbox, and generator) are inspected and maintained with greater frequency, whereas for low-risk components (e.g. brake) the effort is minimized to reduce the total scope of work and cost of maintenance program. In three PhD thesis of Bharadwaj [196], Ramírez [199] and Nielsen [214], several optimum risk-based inspection methodologies have been proposed for offshore wind turbines. Sørensen [29] proposed a risk-based life cycle approach to optimize planning of maintenance in offshore wind farms. The developed approach is based on a pre-posterior Bayesian decision theory which takes into account various deterioration mechanisms such as fatigue, corrosion, wear and erosion. Nielsen and Sørensen [44] proposed an optimal RBM policy for an offshore wind turbine consisting of a single critical component. In their study, the costs related to inspection, repair and lost production under a periodic imperfect inspection policy were evaluated. For more references on RBM models, see [24, 47, 60, 73, 112, 135, 151, 167, 171, 182, 220].

- *Group maintenance, opportunistic replacement*

Under group maintenance policy, the components with similar operating conditions (such as electrical components) are identified and undergo an inspection and maintenance task together. In other words, a group maintenance policy provides a basis to combine maintenance activities and share the set-up costs with a number of components in the system. Such sharing strategy can reduce costs or may result in lower costs compared to the case when maintenance tasks are conducted separately for each component [163]. In opportunistic maintenance policy, an unplanned failure of a critical sub-system is considered as an *opportunity* to perform PM on other sub-systems. One prevalent type of this policy is an opportunistic block replacement policy in which upon a component failure, the whole system is preventively replaced by a new one. For some references on

opportunistic maintenance optimization models, see [38, 51, 55, 118, 131, 132, 162, 164, 172, 173, 185].

7.2. Maintenance effectiveness

Maintenance actions according to degree of restorability of the system are classified into three main categories. The first type of maintenance actions is *minimal* or as bad as old (ABAO), the second class is *complete* (*perfect*) or as good as new (AGAN), and the third class is known as *imperfect* maintenance. Let $\delta \in [0,1]$ denote the effectiveness of a maintenance action. In the ABAO case ($\delta=0$), each repair action restores the system to the level it was just before the failure while in the AGAN case ($\delta=1$), each repair action restores the system to the brand new state. The case $0<\delta<1$ corresponds to imperfect maintenance action in which operating condition of the system is restored to somewhere between AGAN and ABAO. The main advantage of using imperfect maintenance is that the degree of item restoration can be considered a decision variable. Several methods (e.g. the Brown and Proschan, improvement factor, virtual age models) have so far been developed in the literature to model imperfect maintenance. However, the application of these models in O&M planning of wind turbines has been very limited (see [38, 51, 94, 134, 152]).

8. Future research and concluding comments

Even though the maintenance optimization is a relatively young discipline in the wind energy sector, a lot of research has already been done in this field. In the current paper, we proposed a classification framework for the study of inspection planning and maintenance optimization in wind energy industry. The proposed framework identifies various theoretical and practical issues, including the associated models, methods, and the strategies employed by maintenance operators to optimize inspection and replacement decisions in wind energy farms. Moreover, all the academic studies as well as industrial applications reported on the topic over the last two decades were identified, reviewed and analyzed. This classification scheme not only assists researchers in developing novel maintenance optimization methods, but also helps wind energy decision makers (owners/stakeholders) to find the models that fit their specific needs. Based on our findings, the following remarks can be concluded:

(a) Although many good maintenance optimization methods have been developed in literature, there still remains a big gap between academic models and application in practice. Many of the works have been published for mathematical purposes, whereas only very few number of industrial cases (~6% of the total publications) have been presented. A shift from theoretical research to applied research is required. In order to achieve this shift, the availability of real data plays a significant role. Without accurate and precise information, maintenance decisions will be based on wrong or incomplete data which may lead to sub-optimal or even completely wrong solutions. The introduction of computerized maintenance management system (CMMS) such as e-

maintenance technologies can provide a solution to this limitation. E-maintenance has the capability to provide high quality data at the right time in order to make the best decisions for O&M of wind turbines.

(b) Despite the multitude of models available, there is little knowledge on what maintenance strategy is best suited to large-scale wind farms. In order to determine the most cost-effective maintenance strategy, a maintenance optimization model incorporating all information regarding system reliability, failure mechanisms, methods of failure detection, and inspection and maintenance costs is required. This can be achieved using a risk-based maintenance (RBM) approach. However, this approach is very computationally demanding compared to the classical replacement policies. So, there is a need to develop a methodology by integrating the classical approaches and structural reliability analysis that can be used in practice.

(c) Most of the optimization models take into account only one system criterion, either maximizing the reliability or minimizing the maintenance costs. However, in order to achieve the best performance, the reliability/availability measures and maintenance costs should be considered simultaneously. For this reason, the economic added value of optimal maintenance decision on overall performance of the wind farms (in terms of reduction in O&M costs and enhancement in reliability) must be quantified.

(d) Failure modelling and maintenance planning of multi-unit wind turbine systems and structures are quite complicated. Initial (manufacturing-related) defects can occur in any of constituent components and depending on the loading conditions, they can grow to critical size resulting in collapse of the entire system. In many of the existing maintenance optimization models, it is assumed that the failure modes are connected to statistically independent components. However, many failure modes are correlated together due to, e.g. common (uncertain) loading. In many cases, it is imporatant to take this correlation into account. Moreover, some components are exposed to deterioration processes, e.g. fatigue and wear that propagate in time. This time dependency should be modelled, in particular when coupling to condition-based maintenance (CBM).

(e) 'Accessibility' is a very important factor for the ability to perform maintenance tasks on wind turbines. Uncertainty in weather conditions and sea state is a major factor which can affect the accessibility in a wind farm. Meteorological conditions have so far seldom been considered as a stochastic input (see [31, 32]). To improve the existing models, more accurate forecasting tools for wind/wave conditions are required to help the operators in making sound maintenance decisions.

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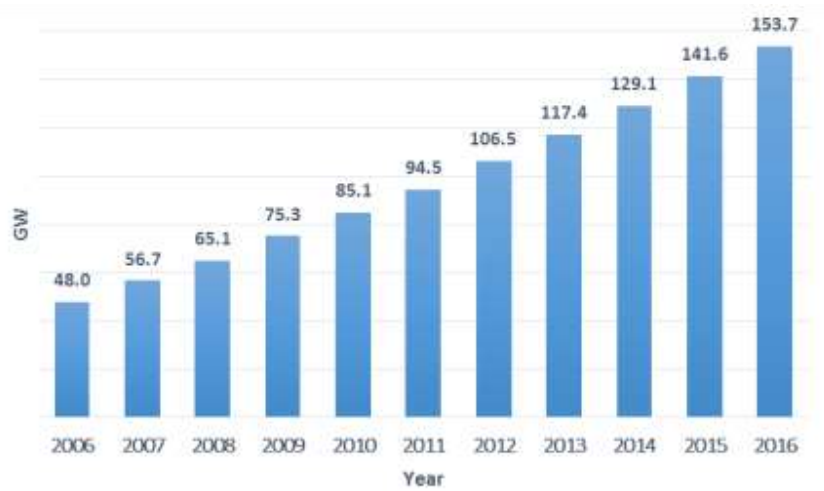
Figure 1. Cumulative installations of wind power in the EU during 2006–2016 [2].
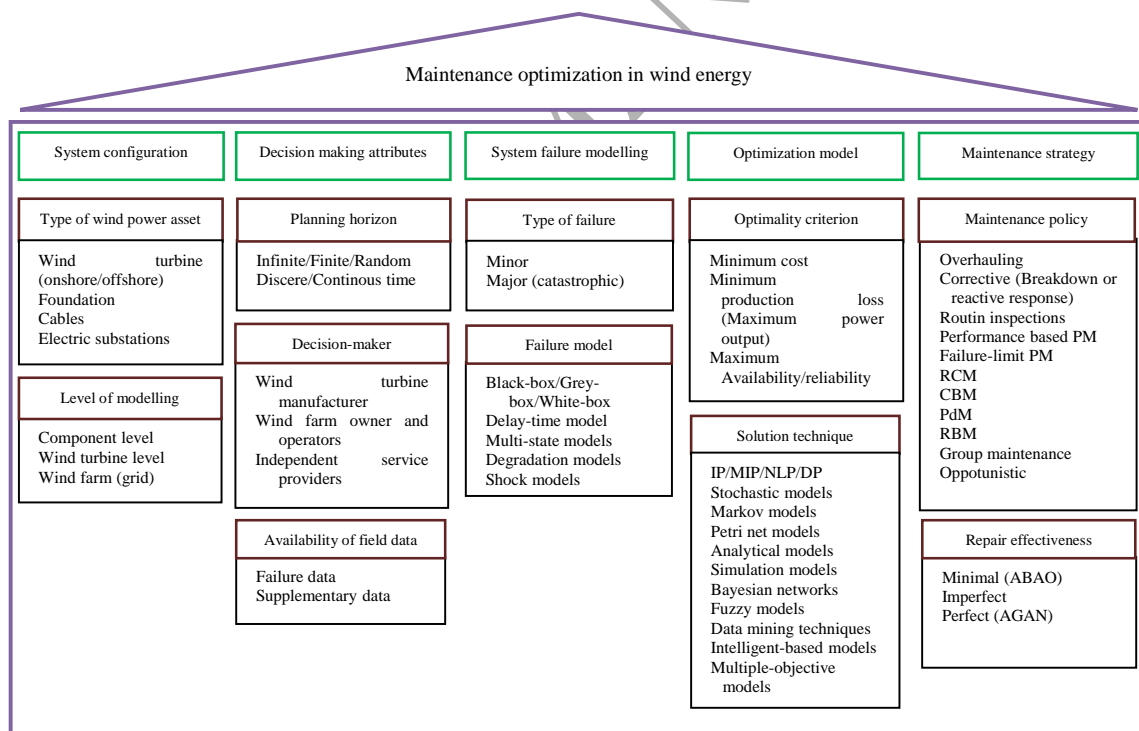
Figure 2. The classification framework proposed for the study.

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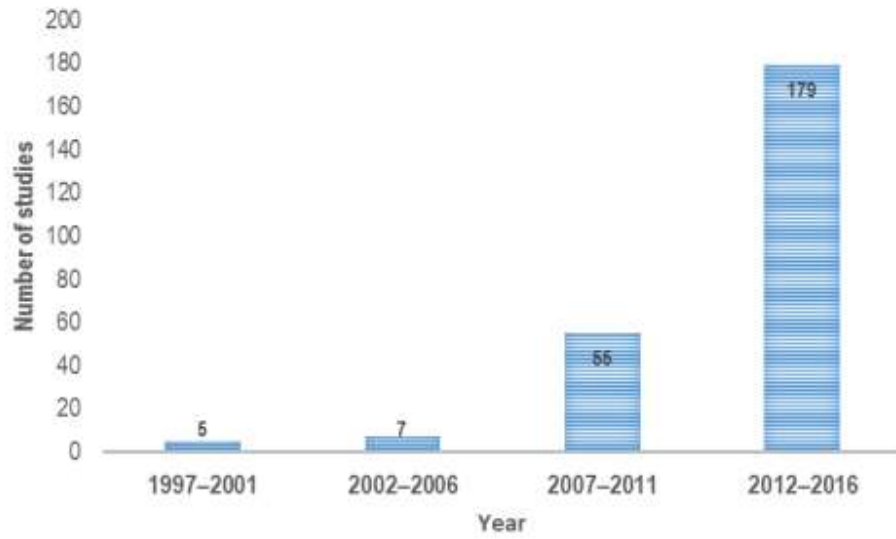
Figure 3. Distribution of the studies by year of publication (1997−2016).

Table 1– Distribution of the journal papers by solution technique and maintenance strategy considered for optimization.

Reference	Solution technique											Maintenance strategy					
	OR (IP, MIP, NLP, DP)	Stochastic models	Markov models	Petri Net model	Analytical models	Simulation models	Bayesian Networks	Fuzzy models	Data mining	Intelligent-based	Multiple-objective	Corrective	Periodic	Failure-limit	RCM / CBM / PdM	RBM	Group maintenance / Opportunistic
Kühn *et al.* [8]						√						√	√				
Ronold *et al.* [9]		√										√					
Ronold and Larsen [10]		√										√					
Verbruggen *et al.* [11]					√							√	√				
Krokoszinski [12]					√							√	√				
Van Bussel and Bierbooms [13]						√						√	√				
Kooijman *et al.* [14]						√						√	√				
Andrawus *et al.* [15]	√					√						√	√				
Andrawus *et al.* [16]	√					√									√		
Hansen [17]					√							√	√		√		
McMillan and Ault [18]			√												√		
Nilsson and Bertling [19]	√														√		
Tavner *et al.* [20]	√														√		

Reference	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Andrawus *et al.* [21]	√													√		
Coolen *et al.* [22]	√													√		
McMillan and Ault [23]		√												√		
Ramírez and Sørensen [24]						√									√	
Veldkamp [25]	√													√		
Wiggelinkhuizen *et al.* [26]					√									√		
Andrawus *et al.* [27]	√											√		√		
Guo *et al.* [28]	√													√		
Sørensen [29]						√									√	
Besnard and Bertling [30]		√												√		
Byon and Ding [31]	√	√												√		
Byon *et al.* [32]		√										√				
Gray and Watson [33]	√													√		
Herbert *et al.* [34]	√										√	√				
Utne [35]				√								√		√		
Yang *et al.* [36]									√			√		√		
Byon *et al.* [37]					√							√		√		
Ding and Tian [38]					√								√			√
Kovács *et al.* [41]	√											√				
Kusiak and Verma [42]								√						√		
Mabel *et al.* [43]				√								√				
Nielsen and Sørensen [44]						√									√	
Tian *et al.* [45]					√								√	√		√
Yang *et al.* [46]			√											√		
Bharadwaj *et al.* [47]				√											√	
Brandão *et al.* [48]									√					√		
D'Amico *et al.* [49]		√												√		
Deng *et al.* [50]	√											√				
Ding and Tian [51]					√								√			√
Feuchtwang and Infield [53]				√							√	√				
Fischer *et al.* [54]	√													√		
Hameed and Vatn [55]	√															√
Hameed and Wang [56]									√							√
Hazi and Gheorghiu [57]					√							√				
Kusiak and Verma [58]								√						√		
Mensah and Dueñas-Osorio [59]					√									√		
Ramírez and Sørensen [60]						√									√	
Scheu *et al.* [61]		√			√							√				
Su and Zhou [62]		√												√		
Su and Zhou [63]	√											√				
Verma and Kusiak [64]								√						√		
Wu *et al.* [65]	√											√				
Zhao *et al.* [66]								√						√		
Zhang *et al.* [67]	√									√		√				
Abouel-seoud and Khalil [68]	√											√		√		
Benmessaoud *et al.* [69]	√				√						√	√				
Besnard *et al.* [70]		√									√	√				
Byon [71]	√	√			√									√		
Carlos *et al.* [72]	√				√							√				
De Andrade Vieira and Sanz-Bobi [73]	√														√	
Dinmohammadi and Shafiee [74]							√							√		
Dinwoodie *et al.* [75]					√	√						√				
Grecchi *et al.* [76]					√							√				

Halvorsen-Weare *et al.* [77]	√							√		
Hameed and Wang [78]						√				√
Hofmann and Sperstad [79]				√			√	√		
Huang *et al.* [80]				√				√		
Jin *et al.* [81]	√						√	√		
Kahrobaee and Asgarpoor [82]			√	√				√	√	
Li *et al.* [83]					√			√		
Nguyen *et al.* [84]					√	√		√		
Pan *et al.* [85]	√				√		√	√		
Perez-Canton and Rubio-Romero [86]	√							√		
Schlechtingen *et al.* [88]					√	√			√	
Shafiee *et al.* [89]	√							√	√	
Sinha *et al.* [90]						√			√	
Smarsly *et al.* [91]						√			√	
Smarsly *et al.* [92]						√			√	
Tracht *et al.* [93]					√			√	√	
Van Horenbeek *et al.* [94]		√		√					√	
Wang *et al.* [95]	√			√				√		
Costa *et al.* [96]				√					√	
De Prada Gil *et al.* [97]				√			√	√		
Ding *et al.* [98]	√			√					√	
Dinwoodie and McMillan [99]				√			√	√		
Fathi Aghdam and Liao [100]	√							√	√	
Fonseca *et al.* [101]	√							√		
Griffith *et al.* [102]				√					√	
Haddad *et al.* [103]				√					√	
Hong *et al.* [105]	√							√		
Kang *et al.* [107]						√			√	
Li *et al.* [108]				√		√			√	
Ma *et al.* [109]						√			√	
Nejad *et al.* [110]		√						√	√	
Netland *et al.* [111]				√					√	
Nielsen and Sørensen [112]					√					√
Ortegon *et al.* [113]				√			√	√		
Réthoré *et al.* [114]							√		√	
Sainz and Sebastián [115]				√					√	
Sinha *et al.* [116]				√					√	
Sperstad *et al.* [117]				√				√		
Su and Chen [118]		√								√
Sun *et al.* [119]				√				√		
Tao and Zhou [120]		√							√	
Wang *et al.* [121]		√						√		
Wang *et al.* [122]						√			√	
Yampikulsakul *et al.* [124]				√					√	
Yang *et al.* [125]				√					√	
Zhang *et al.* [127]		√						√		
Zhang *et al.* [128]			√	√				√		
Zhang [129]	√							√		
Zhang and Wang [130]						√			√	
Zhao *et al.* [131]	√									√
Zhao and Zhang [132]	√									√
Zheng *et al.* [133]			√					√		
Zhao *et al.* [134]	√								√	

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	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Zhou *et al.* [135]					√										√	
Asensio *et al.* [136]					√	√								√		
Astariz *et al.* [137]					√							√				
Astariz *et al.* [138]					√							√				
Astariz *et al.* [139]					√							√				
Booma *et al.* [140]	√										√	√				
Chen *et al.* [141]						√						√				
Costa *et al.* [142]					√								√			
Cross and Ma [143]								√						√		
Dai *et al.* [144]	√											√				
Dalgic *et al.* [145]						√						√				
Dalgic *et al.* [146]						√						√				
Dalgic *et al.* [147]						√						√				
de la Hermosa González-Carrato *et al.* [148]									√					√		
Dinwoodie *et al.* [149]						√						√				
Dumitrascu *et al.* [150]						√								√		
Florian and Sørensen [151]						√	√							√	√	
Florian and Sørensen [152]					√	√							√			
Gundegjerde *et al.* [153]		√														
Igba *et al.* [154]	√					√										
Jin *et al.* [155]	√											√				
Jin *et al.* [156]										√		√				
Joschko *et al.* [157]						√					√	√				
Kerres *et al.* [158]		√												√		
Liu and An [159]					√						√	√				
Pérez *et al.* [160]						√					√	√				
Santos *et al.* [161]						√					√	√				
Shafiee and Finkelstein [162]	√	√														√
Shafiee and Finkelstein [163]	√	√														√
Shafiee *et al.* [164]	√	√														√
Shafiee *et al.* [165]	√					√						√				
Singh *et al.* [166]									√					√		
Sinha and Steel [167]					√									√		
Stålhane *et al.* [168]	√											√				
Catterson *et al.* [169]					√							√				
Le and Andrews [170]		√												√		
Gintautas *et al.* [171]						√								√		
Abdollahzadeh *et al.* [172]										√						√
Atashgar and Abdollahzadeh [173]										√						√
Baglee *et al.* [174]									√					√		
Lahcen [176]			√								√	√				
Lei and Sandborn [177]						√								√		
Leigh and Dunnett [178]				√							√	√		√		
Li *et al.* [179]		√									√	√				
Martin *et al.* [180]					√	√						√				
Nicolas and Dominique [180]						√								√		
Ossai *et al.* [182]			√													√
Pattison *et al.* [183]									√					√		
Pliego Marugán *et al.* [184]					√								√			
Sarker and Faiz [185]	√															√
Zitrou *et al.* [186]		√									√	√				