Framework for managing the operations and maintenance of wind farms

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Abstract. The operations and maintenance of a wind farm constitutes a considerable source of expenditures therefore a holistic framework is herein presented aiming at optimising their management. The principles upon which the framework was developed belongs to the asset management discipline oriented towards the wind energy sector. Besides, it is understood from a cross functional perspective which also embraces information management and business aspects. The framework comprehends different modules conceived with the following purposes: (i) creation of an integral and comprehensive failure database, (ii) modelling of the wind turbines' reliability taking into account their operational context and (iii) defining of maintenance strategy within a life-cycle perspective. The practical aspects of the framework are demonstrated through a case study based on real-field data from the sector. Furthermore, the present research sets the foundation to consider all the proposed algorithms, processes and techniques within a Product-Service System approach, which entails important benefits for the OEMs an for the operators.

1. Introduction
The increasing importance and development of the energy sector in terms of installed capacity and technological solutions have arisen new challenges to face, in particular, related to asset’s reliability and wind farm logistics [1]. In Europe, wind energy is the second largest form of power generation taking into account onshore and offshore wind farms. Operations and maintenance costs associated with onshore and offshore wind farms may rise to 32% and 12-30% of the total life-cycle cost of the wind farm respectively [2, 3]. It is reasonable to strive for reducing the operations and maintenance costs, but it is important to bear in mind that availability is a must to ensure the wind farms profitability. In such context, asset management stands as an advantageous discipline to maximize the profitability of the investment, a proper maintenance strategy helps to reduce maintenance costs whilst improving availability [4, 5].

Nowadays, the massive amount of data available may be transformed into useful information which may serve as a solid basis to optimize maintenance strategy. In order to translate the data into valuable information from the maintenance strategy perspective, reliability engineering provides useful techniques which allow characterizing the wind farm and wind turbines behaviours from operational data. Therefore the optimization of the maintenance strategy for the life-cycle of the wind farm is a heavily based data-driven decision-making process. This reality positions the Original Equipment Manufactures in a favourable position, their insights of the asset and its management enable an offer based on knowledge-intensive products and services which provide an important competitive advantage [6, 7]. This fact has
given rise to Product-Service-Systems (PSS) where both, product and services, conform a single offer. PSS business model entails a closer relationship between the OEM and the customer bringing additional value to both.

In order to support the developments in the sector, the new emerging technologies and the PSS business models in the asset management field, the authors have conducted the research summarized in this paper. The main contribution here presented consists of a framework that comprehensively integrates data-structure and asset management innovations for maintenance strategy optimization within the scope of PSS business model for the wind energy sector.

1.1. Related works
In the literature, the reliability approach has proven useful when optimizing the definition of maintenance strategy [8]. In order to carry out a reliability study, the relevant information needed as an input to the decision should be at hand, in the right format and on time [9]. The creation of a common database for the wind energy industry is not a new problem in the literature, a description of the objectives of a Reliability-Availability-Maintainability (RAM) database in the sector can be seen in Hameed et al. [10] and in Zhao [11]. In the previous work, the challenges for creating such database are addressed by considering information sources such as operational data, equipment data, failure data, maintenance data and state information [8].

The need to integrate data coming from different sources with operations and maintenance purposes is also stated in [12], in order to exploit the value contained in that information it is critical a correct assessment of the failure process and therefore the selection of the proper time-to-failure model [13].

In the context of this paper, the reliability study of the wind turbines has to be performed under several conditions regarding data quality and quantity [8]. In order to achieve the required data standards, it is possible to combine data from similar assets [13, 14]. However, it is important to consider that some wind turbines may present different failure behaviours and frequencies caused by the operational conditions [15, 16]. In such context, it is important to take into account the reliability models which considers the influence of operational environment as well as dynamic conditions like the ones in [17, 18, 19]. The integration of operational context information, as well as dynamic considerations, has proven to provide more accurate reliability estimates and therefore better results of the maintenance strategy [18, 20]. In the literature, it can also be found research works which provide evidence of the improvements in the maintenance strategy by the integration of reliability models with clustering algorithms to deal with heterogeneity in failure behaviours [21, 22].

These reliability models serve as a valuable input in order to customize maintenance plans, which will be highly conditioned by the chosen maintenance policy [23]. The chosen maintenance policy has to be aligned with the organizational goals [24] and has to consider the specific aspects of the assets. One of the most studied maintenance policy in the literature for wind farms is the opportunistic maintenance [23]. The opportunistic maintenance policy makes the most of short-term situations to perform preventive maintenance on a system when corrective maintenance is needed in another one: the decision is grounded on a threshold regarding system’s age, reliability or health. Besides, opportunistic maintenance is attractive in the context of wind energy sector because it considers wind turbines having economic, structural and stochastic dependencies [25, 26]. Some research of special interest can be seen in: the work of Erguido [26], where the maintenance plans are optimized for Lifecycle Cost (LCC) and availability according to weather conditions; in [27, 25] a multi-objective optimization is also propose to minimize maintenance cost and loss of production by grouping the WTs and their maintenance tasks; and the work of [28] explore the differences among opportunistic maintenance and two alternative maintenance strategies.

In the previous works, the optimization of the maintenance strategy is sought for the lifecycle
of the assets. This life-cycle perspective is aligned with seeking recurrent income in the long-term whilst reducing costs, to this aim, it has attracted some attention the study of the conjoint offer of product and services known as Product-Service System (PSS) [29]. Moving towards a PSS business model ensures customer relationship as a competitive strategy [30] while the asset management discipline guarantees product performance and operational excellence [31], therefore aligning operational and strategic objectives. This comprehensive view of the maintenance strategy is supported by asset management discipline, accordingly, its importance its recognize by The International Standards Organization in [32] as well as by other asset management frameworks like2 [33, 35, 34].

1.2. Motivation, contribution and overview

It is the scope of this paper to provide a managing framework which helps OEMs and operators of wind farms dealing with operations and maintenance. The comprehensive approach aims at contributing with a cross-functional value proposition which starts by defining the data structure and database needs. Then, it provides guidelines on reliability engineering to describe the behaviour of the wind farm following a structured procedure and thus, enabling the optimization of the maintenance plans and a LCC analysis for the defined strategy. Besides, the approach is considered within the context of PSS scenarios, these scenarios entail services associated with the wind turbines which may condition the most favourable scenarios not only for the operator but for the manufacturer as well.

The contribution of the framework lies within the proposal of a management framework that integrates specific tools, mechanisms and algorithms in order to optimize the maintenance of a wind farm. Compared to other frameworks in the literature (see for instance [34, 33]), it provides a more pragmatical point of view facilitating its integration in the industry. Meanwhile, compared with more technical research regarding algorithms and specific methods, it contributes with a strategic view that provides the alignment among the mathematical methods and the organization goals enabling higher profitability.

In the remaining of the paper, the framework is first presented in section 2 and then every aspect of it is further explained in the corresponding subsections. The development of every aspect of the framework is set out from a managerial perspective but, in order to favour the applicability of the research, specific tools, algorithms and techniques are proposed as a guideline to serve the managerial purposes. As an example of the application of the framework, a case study is presented in section 3. In section 4 the results of the case study and the benefits derived from the implementation of the framework in the management of wind farms are discussed, they are mainly related to revenue, service level and maintenance optimization.

2. Proposed Framework

The presented framework is a holistic proposal whose departure point is the definition of the structure and information of the database needed for the reliability analysis of the wind turbines. Providing that the reliability of the wind turbines has been properly calculated and that it integrates the information regarding the operational environment of the wind turbines, the next stage consists of the definition of the optimal maintenance strategy. The maintenance strategy is determined by means of an optimization procedure embedded not only with the mathematical algorithms but with the logic proposed by dynamic opportunistic maintenance as well. Finally, the characterization of the wind turbines failure behaviour and the definition of certain maintenance strategy allow calculating the life-cycle costs (LCC) of the wind farm. The LCC calculation is performed by means of simulation tools, they have proven useful when determining the RAM statistics during the life-cycle as well as other important Key Performance Indicators (KPI) of the business.
It is important to take into consideration that this cross-functional approach is contemplated into a business model focused not only on selling products but the services associated with them as well. Therefore the framework is proposed aiming at enabling the organizational shift needed to maximize OEMs profitability and customer satisfaction. In Figure 1, a graphical representation of the framework can be seen and in the following subsections, every stage of the framework is further explained.

Figure 1. Proposed framework

The framework representation not only includes the process to manage the maintenance and operations of wind farms, but it also gathers the inputs needed in every stage in terms of information, tools and techniques.

2.1. Failure database
Information and data quality are two of the essentials aspects to consider in every decision-making process, in the proposed framework the construction of a failure database is proposed as the starting stage.

As an initial step, it is important the definition of failure modes and their association with maintenance actions. The definition must ensure coherence among the maintenance actions indenture level and the failure modes of the components. Having defined them it is possible to deal with the historical records in a structured form.

In order to identify the failures modes in the records and information coming from the SCADA system, it is necessary to match the alarms with wind turbines states and functional failures whilst bearing in mind aspects concerning data scarcity, data censoring, data pooling and the effect of repair actions.

As the proposed reliability models integrate information regarding the operational context it is therefore vital that the failure database also includes the environmental conditions under which the wind turbines have been operating. Accordingly, in the framework, it is proposed to link the failures, alarms and states of the wind turbines with their specific operational condition which may influence the failure behaviour.
Once the database has been built and the data in it contained is consistent and represent the true behaviour of the wind farm, it is possible to select and fit a proper reliability model to exploit and understand the inherent value of the data.

2.2. Reliability of wind turbines
In an initial attempt to model the reliability of the components of the wind turbines, it is possible to rely on clustering approaches. In the proposed model, the k-medoids clustering algorithm is proposed as a mean for determining possible groups of turbines with different statistical behaviours.

One of the key pillars when adjusting the reliability model for each detected segment is the identification of the reliability driver, the variable that most conditions the component degradation and failure. It is of vital importance because it will be the variable to control since it will trigger the maintenance actions. However, failures are not exclusively affected by one variable; the characteristics of the operational environment in which the wind turbines operate affects their reliability and therefore their failure frequencies and behaviours.

Reliability models that take into account the operational context such as the Weibull Proportional Hazards Models are proposed. In advanced reliability models which harvest the capabilities of machine learning algorithms, it is also possible to consider the changes of the operational context overcoming the assumption of constant working conditions. These models enable to customize the maintenance strategy according to the working environment of the wind turbines establishing a differential competitive advantage, not only in the operations management but in the offer stage as well.

2.3. Maintenance strategy
In the paper, it is proposed to optimise the maintenance strategies based on previous reliability analysis since it allows assessing the risk of failure in every component. The identification of components’ reliability in their specific operational context will enable to further optimise maintenance strategy.

The approach proposed for the maintenance strategy is dynamic opportunistic maintenance, it is especially interesting because it allows considering the economic, structural and stochastic dependencies among the components. In the proposed strategy different maintenance levels (imperfect/perfect) are defined which have associated certain reliability threshold. The different maintenance activities are triggered according to the reliability threshold, and the strategy considers the possibility of grouping several maintenance activities in order to optimize cost and performance. In order to integrate such considerations, dynamic opportunistic maintenance takes into account short term information regarding both internal and external factors, providing therefore, better decisions.

It is critical, given the nature of the dynamic opportunistic maintenance, to use simulation techniques to evaluate maintenance decisions according to their cost, availability or other key performance indicators. Consequently, it is necessary to develop simulation-based optimisation mechanisms, which will enable the combination of the simulation model developed for evaluating maintenance decisions and advanced meta-heuristic optimisation algorithms, such as particle swarm or genetic algorithms. Particularly, and considering the several objectives pursued in the context of maintenance and services, multi-objective optimisation algorithms should be implemented; they will allow decision-makers finding a trade-off among conflicting objectives and representing the objectives in their decisions.

Generally, in the case of Wind Farms, the conflicting interests regarding maintenance are due to the loss of production caused by the performance of maintenance actions, either corrective or preventive. The service-level disruptions caused by preventive maintenance actions are directly related to the service-level disruptions caused by the failure of components, i.e. the
more preventive maintenance actions the fewer failures are likely to occur. Accordingly, the multi-objective techniques allow for balancing the service-level disruptions, which entail loss of production, with the life-cycle cost of the Wind Farm. The output of the multi-objective optimization will allow to select among several non-dominated solutions in which the service level cannot be improved without increasing the costs, thus a trade-off has to be chosen from the Pareto optimal solutions (all possible non-dominated solutions).

2.4. **LCC Analysis**

Regardless of the nature of the objectives that aforementioned maintenance strategies pursue, the decisions to be made should regard at the whole life cycle of the wind turbines, ranged between 20 and 30 years-long. In this context, it is critical to derive the simulation models so that the performance measures are evaluated along the assets’ life cycle. Therefore, aided by the maintenance strategy derived in subsection 2.2, the simulation model should characterize the malfunction of the assets in a specific operational context and estimate the implications of operation and maintenance activities’ planning in the corresponding KPIs.

A particularly interesting technique that lays the foundations for calculating such measures is life cycle costing, which attends both capital expenditures (CAPEX) and operational expenditures (OPEX). Capital expenditures correspond the ones related to the construction and installation of wind farms, including the cost of the turbine itself, its transportation, grid connection, civil work, R&D, etc. On the contrary, operational expenditures regard to the wind farm operation and maintenance, insurance, taxes, management, administration, etc. As a consequence, making decisions attending to both expenditure categories will significantly enhance not only operational decisions, but also strategic decisions, such as maintenance or investment planning respectively.

It should be noticed that this life-cycle cost analysis is critical to shift to service-oriented business models, such as wind farms performance-based contracting, where instead of selling wind turbines it is the energy they provide what is sold. In this context, asset management strategies enable the conjoint optimisation of LCC and RAM indicators, which is vital to find an accurate estimation of wind farm cost and service level along its life-cycle. Accordingly, previously derived dynamic opportunistic maintenance strategies have been complemented through the integration of the analytical modelling of wind farms CAPEX and OPEX in the simulation-based optimisation mechanism. As a result, optimal strategies that lead to highly efficient maintenance policies in terms of achieved energy-based availability and costs have been found, laying the foundations for defining an attractive service-oriented offer.

The approach, algorithms, techniques and tools proposed in the framework allows considering multiple PSS scenarios. By introducing changes in the simulation model and/or the cost structure it is possible to evaluate several offers which may entail different services. The proper characterisation of the wind turbines behaviour, as well as the definition of the maintenance strategy, allows to asses every scenario from a transparent and comprehensive perspective.

Nevertheless, the uncertainty sources and the stochastic nature of the algorithms and processes involved render non-deterministic solutions which may put at risk the profitability of chosen PSS. To overcome that difficulty, the framework considers uncertainty analysis that assesses the possible deviations from the different solutions and scenarios. By integrating the uncertainty analysis a risk-based decision approach is enabled, thus the results in terms of costs and services are enhanced since the decision making process regarding the operations and maintenance of wind farms is supported by a more solid knowledge.

3. **Case Study**

The proposed framework has been validated through a case study in the wind energy sector. From real field data, the life cycle of a wind farm has been simulated, i.e. 20 years of operation.
In order to optimize the maintenance strategy to be adopted in the operation of an onshore WF, a simulation based-optimization with the NSGA-II algorithm has been conducted. The Pareto optimal of maintenance strategies has been determined, in it four components, with three different failure modes each, are considered according to their criticality in terms of availability and costs: the gearbox, the blades, the pitch system and the yaw system. The multi-objective simulation seeks to minimize the OPEX of the WF whilst minimizing the loss of production for the life-cycle of the turbines, the Pareto optimal yielded by the optimization of the maintenance strategy can be seen in Figure 2. The maintenance strategy studied is the dynamic opportunistic maintenance, it determines whether to perform or not maintenance actions according to dynamic reliability thresholds that take into account the operational conditions of the WTs. As it can be seen in Figure 2, once the client has defined certain service level and certain OPEX they are willing to assume, it is possible to see the possible maintenance policies fulfilling such criteria. And it is also possible to determine those maintenance solutions which are unfeasible in terms of availability and price.

In order to provide deeper insights into the performance of the proposed approach, it is compared against static opportunistic maintenance and against a corrective strategy. To such aim one of the policies has been chosen a simulated through the life-cycle of the WF while comparing it with the other strategies. The results are represented for the objective functions of the multiobjective optimization, i.e. loss of production and OPEX. The representation of the results can be seen in Figure 3.

As it can be seen in the graphs, both of the opportunistic maintenance strategies yield better results in the OPEX objective than the corrective strategy. It is due to a correct assessment of the WT reliability taking into account the operational context, therefore the preventive maintenance actions are performed in the proper moment. Besides the dynamic opportunistic maintenance outperforms the static strategy when minimizing the loss of production because the actions are performed in those periods of time when it is more favourable for the business.

4. Concluding Remarks
The present paper proposes a comprehensive framework which aims at facilitating the management of operations and maintenance of wind farms. This holistic proposal covers several realities of interest regarding operations and maintenance; it deals with data structure and needs,
Figure 3. Results of the comparison

mathematical modelling of failure behaviours according to operational context, optimization of maintenance actions within a life-cycle perspective whilst maintaining desirable service levels and LCC calculation from a risk-based decision approach. Besides, the framework considers these realities within the context of servitization and therefore it provides a PSS business model perspective. The implementation of this value proposition in the management of wind farms will bring several benefits in terms of:

a. **Optimised maintenance**-Since the failure behaviour of the asset is characterized according to operational context, the maintenance actions are performed in the most appropriate time. The dynamic opportunistic maintenance allows grouping several maintenance actions in order to improve costs and availability. This is all considered not in the short term but for the whole life cycle of the wind turbines as it can be seen in the case study.

b. **Lower costs**-A better assessment of the WTs reliability leads to the optimisation of the maintenance actions entailing a cost reduction since the cost structure of the activities is considered and implemented in the simulation models. The improved characterisation of the failure events reduces also the costs derived from unavailability or security issues.

c. **Higher availability**-The optimisation is multi-objective, which implies that in spite of the cost reduction the service level provided by the wind farm will be maintained within the
desirable levels. Ensuring OEM’s and operator’s satisfaction during the life-cycle of the project.

d. Increased income—The improvements in availability ensure higher incomes. But the consideration of the framework within the PSS business model ensures recurrent income derived from the service offer. The income from the services ensures long term revenue for the OEM whilst maintaining customer satisfaction.

e. New services offer—By the simulations tools the OEMs can assess the offer of the new services they are interested in selling. They can provide the information rendered by the simulation in terms of KPIs to the customers. This information will present the new services offer in a transparent way such as the Pareto Optimal, which facilitates the sale of the new services and promotes loyalty and trust relationships.

f. Investment opportunities—The OEMs can use the provided tools in order to assess the profitability of possible investments from a risk-based decision-making approach. It is possible to see how investments in improving certain aspects of the wind turbines, e.g. component reliability or maintainability of failure modes, impact on the cost-performance metrics of the wind farm for the life-cycle.

The research herein presented is a step forward in the alignment of strategic and operational management by the proposal of a framework that integrates specific technologies across the different disciplines involved in the servitization process. The PSS business model considered in the framework facilitates the decision-making process of the OEMs and it provides multiple advantages, not only for them but for their clients as well. Highlighting the main advantages, it is remarkable how the maintenance strategies are aligned for the OEM, the client and the asset; the deployed technologies ensure that the operations provide the desired service level at an affordable cost; and the close cooperation between the OEM and the client results in a better feedback process with effects on product design, know-how, services offer and loyalty.

In fact, the principles in which PSS is based allow to identify and satisfy the clients’ needs in terms of transparency, availability and product knowledge, whilst the innovative asset management technologies addressed allow the manufacturer to maintain his business profitability by optimizing costs. However it is important to bear in mind that further efforts are encourage to provide and develop more technological tools, algorithms and process to support the servitization process for OEMs, helping to overcome the barriers that hinder the adoption of PSS business models.

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