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Prescriptive Maintenance for Onshore Wind Turbines

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Abstract

Electricity generated by wind turbines (WT) is a pillar of the transition to renewable energy [1]. In order to economically utilize WTs, operating and maintenance costs, which account for 25% of total electricity generation costs in onshore WTs, are a focus of cost reduction activities [2]. A prescriptive maintenance approach can support in achieving this goal. Prescriptive maintenance is a maintenance approach, where asset condition data is collected and analyzed to recommend specific actions to prevent breakdowns and reduce downtimes. However, the processing and analysis of data is quite complex. Especially unstructured data (such as comments of service technicians in free text fields) is often left unused, as companies, mostly SMEs lack the capacity to carry out these analyses. In this work we propose an approach to utilize the information from service reports, maintenance reports as well as status records from SCADA systems for the development of a prescriptive maintenance approach to onshore WTs. To achieve this, an ontology was utilized in this approach to codify implicit knowledge of service technicians and aid in making unstructured data usable for further analysis. The ontology was used to link historical service and maintenance reports with status codes, thus enabling automated analysis. In interviews with WT topic experts and through further research, damage mechanisms and corresponding maintenance measures were identified and a measure catalogue was developed to support service and maintenance activities. The recognition of the root cause of problems allows for a prescriptive maintenance approach that recommends targeted actions to reduce downtimes and optimize maintenance activities, it also allows to effectively control the outcome of maintenance activities and optimize their execution.

Keywords

Prescriptive Maintenance; Ontology; Data Analytics

1. Introduction

Electricity generation from renewable energies continues to gain importance in Germany, surpassing electricity generation from fossil fuels for the first time in 2020 [3]. The largest share (41.7%) of electricity generation from renewable energies comes from onshore wind turbines (WTs) [4]. This highlights the key role of onshore WTs in achieving an environmentally friendly energy supply for Germany. One of the biggest challenges for operators of wind turbines (WTs) is the increasing cost pressure [5]. This is primarily caused by 2 factors: the expiration of the EEG (German: Erneuerbare Energien Gesetz; English: German renewable energy law) subsidies and increasing operating and maintenance costs (O&M costs) as the turbines age [6–8]. While the annual O&M costs of a new turbine are still at 10 to 15% of the average total costs per kWh, this share rises to as much as 35% by the end of its service life. On average, the O&M costs thus make up about 25% of the total costs per kWh [2]. This makes O&M costs a powerful lever for reducing the power generation costs of onshore WTs.

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Maintenance activities include upkeep, inspection, repair and improvement [9] and usually take place at fixed intervals according to predefined maintenance specifications. This is where a promising new approach to reducing maintenance costs comes into play: the condition-based maintenance strategy [10]. Such a strategy is aimed at optimizing maintenance activities for time and personnel utilization, depending on the system and life cycle phase [10]. The basis of such maintenance optimization is detailed knowledge regarding the condition of the WT. For this purpose, large operators of wind farms or manufacturers of WTs evaluate operating and structured data from the maintenance history, but small and medium enterprises (SMEs) do not always have the capacities for such an evaluation. Regardless, comments on the condition of the turbine are often not used at all. These comments are often contained in non-standardized form in service reports and are documented by service technicians in free text fields. The latter are used to record the experience of service technicians in the otherwise standardized service reports. However, especially against the background of the increasing importance of interconnectedness and information processing in the yield and maintenance cost optimization of WTs, these sources of information are becoming more and more important. The possession of data and the ability to use it as a base for decisions on process optimization brings decisive cost advantages in the highly competitive energy sector.

This is exactly the lever, which the research project “ReStroK” targets. Together with partners from research and industry, the Institute for Industrial Management (FIR) at RWTH Aachen University is investigating the machine evaluation of both status data and maintenance histories, which have so far been used primarily for documentation purposes. The focus is on the avoidance of breakdowns due to progressive wear and tear of individual components by timely and effective maintenance of these components.

In the context of ReStroK a procedure for converting the information contained in the free texts of service reports regarding the turbine condition into a usable form was developed. This was realized, based on a previously developed specialized ontology [11]. The focus of this paper is however the damage mechanisms in onshore WTs and corresponding maintenance measures. In interviews with WT topic experts and through further research, failure modes were linked with optimized maintenance measures, and a measure catalogue was developed to support service and maintenance activities. In a first step, the analysis focused on the pitch system as well as the converter.

2. State of the art

2.1 Prescriptive maintenance

In the context of Industry 4.0, a distinction is made between different development stages. First, visualization and transparency are used to identify what is happening and why. Then prediction and finally self-optimization is made possible through data analysis and digital connectivity [12]. According to Davenport, within these stages of development, there are several levels of competitive advantages that can be achieved through business intelligence and analytics (Figure 1). The highest being the use of analytics for optimization of business activities, such as maintenance [13].

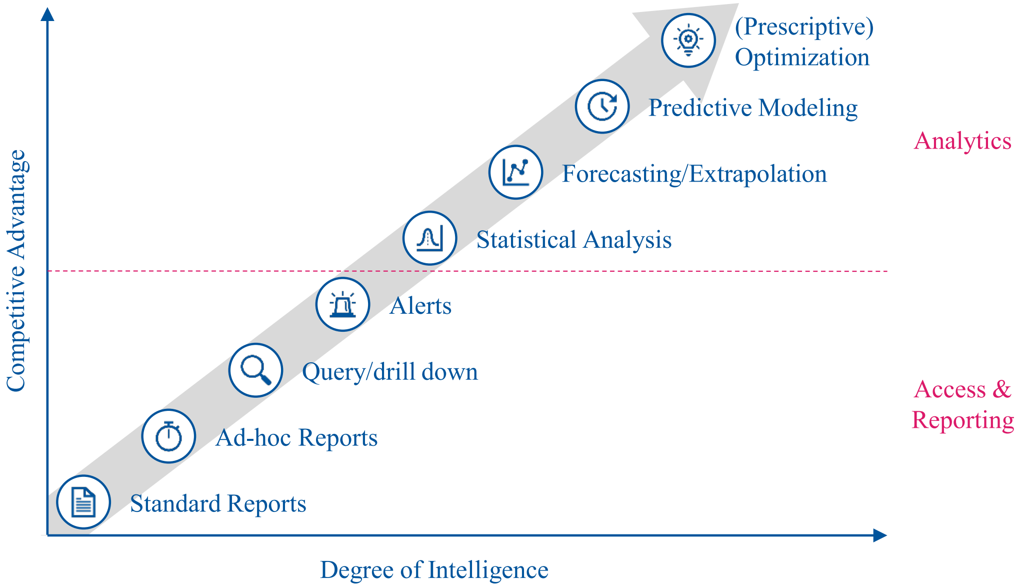

Figure 1: Business intelligence and analytics (Source: own representation based on Davenport [13])

Maintenance activities can be clustered in corrective (after fault occurrence) and preventive maintenance (prior to fault occurrence). Predictive maintenance approaches, a sub-set of preventive maintenance aim to carry out maintenance activities derived from data analytics and evaluation of significant system parameters [14]. However, predictive maintenance approaches are further differentiated. One such extension is the prescriptive maintenance approach. Whereas in a predictive maintenance approach only the condition of the object of maintenance is considered to carry out maintenance activities based on a forecast, a prescriptive maintenance approach considers the object of activities to be a guiding and controlling element for activities as well [15]. Such a maintenance approach would not just include the performance of maintenance activities prior to fault occurrence but also prescribe recommendations for specific actions to prevent breakdowns and reduce downtimes. A prescriptive maintenance approach, includes the collection of data of significant parameters, its analysis and evaluation and finally the utilization of these insights to prescribe activities to the object of the maintenance strategy. Based on data, measures are prescribed, evaluated for effectiveness on the object of maintenance activities and adapted when needed. This achieves the highest level of maturity and competitive advantages for a system, to be self-optimizing [13,16]. The basic data framework in such a prescriptive maintenance approach is shown in Figure 2.

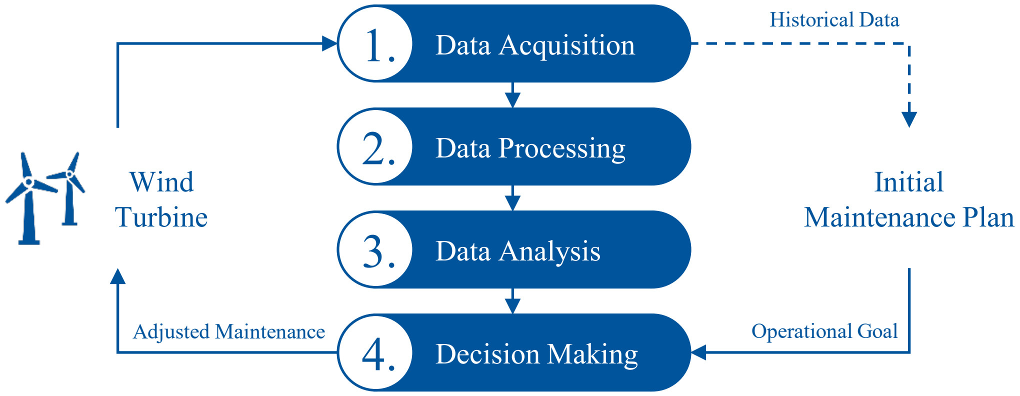

Figure 2: Data framework in a prescriptive maintenance approach (Source: own representation)

2.2 Utilization of data for maintenance of wind turbines

In order to implement a prescriptive maintenance approach with its inherent optimization characteristics, it is necessary to access and evaluate data of the object of activities [17]. Onshore WTs collect and transmit a variety of different data that can be used for prescriptive maintenance. These data are the master data of the WT, operating data sourced from Supervisory Control and Data Acquisition Systems (SCADA), which in part comprise hundreds of measuring channels, status and alarm messages as well as event and maintenance data, and data from the component-specific condition monitoring system (CMS) [18]. Previous approaches to optimize the maintenance of onshore WTs focus mainly on the analysis of data from the SCADA system and CMS. Comparatively little attention is paid to the maintenance data from service reports, which are at the center of the optimization approach developed in the context of “ReStroK”.

The reasons for the nonuse of data are manifold. On the one hand, inadequate organizational structures may hinder the evaluation of already existing data, on the other hand, data may not be usable at all, since, for example, maintenance histories are often available in different formats such as paper or PDF. In addition, numerous different actors are involved in the various stages of a WT's lifecycle, further amplifying the problem of different data formats and data bases. In the context of prescriptive maintenance, the operating phase is of particular interest. This phase is characterized by a “service network” consisting of the operator, independent service providers (ISPs), OEMs and suppliers [19]. Especially OEMs and ISPs are often in direct competition with each other [20]. For this reason, there is usually little to no exchange of data and/or knowledge, which would be essential for targeted optimization of maintenance. As a result, hardly any technical system structures and standardized event classifications for the recording, storage and use of event data or information from service reports that are accepted throughout the industry exist. Conversations and interviews with OEMs and ISPs confirm, that software systems are mainly used for the documentation towards operators. Some specific concepts have already been developed and implemented together with expert committees, which, adapted to the needs of the wind energy industry, should enable cross-company work [10,21]. Examples of such standards are the internationally standardized reference designation system for power plants (RDS-PP), the state-event-root cause key for power generation units and the Global Service Protocol as a technical guideline of the Födergesellschaft Windenergie (FGW). However, our research data shows, that from the OEMs and ISPs perspective the effort to implement the systems mentioned above is not always worthwhile. In addition, OEMs and ISPs often already have their own systems and the ability to perform in-house analysis. Accordingly, industry-wide cooperation and increased transparency is seen as a disadvantage for their own competitive position. This poses a major challenge for SMEs in particular, as they were often found not to have the appropriate capacities for in-house data analysis and maintenance optimization.

Faulstich and Hahn however, point out the added value of an evaluation of event data [18]. Event data on the one hand includes the automatically generated status messages of the WT and on the other hand maintenance data from service reports. Status codes report status changes of the WT and can thus indicate necessary maintenance measures. The corresponding status codes already provide information about the affected systems. Yet, often there is no clear assignment of a faulty condition to a causal component. Rather, as confirmed by interviews with ISPs, it is a “black box” containing a number of different components that may have caused the fault.

To overcome this challenge an ontology is needed. “An ontology is a formal, explicit specification of a shared conceptualization” [22]. In the specific use case for the service reports of onshore WTs, this means that the ontology is suitable as a link and common language between service technicians or maintenance reports and the SCADA system or status codes. Various approaches to ontologies can be found in the literature. For example, Zhou et al. developed an ontology based on Failure Mode and Effects and Criticality Analysis (FMECA) [23], Papadopoulos and Cipcigan developed an ontology that can be used for gearbox failure detection and diagnosis [24], and Ertek et al. performed an ontology-based analysis of the external circumstances and environmental conditions of WT accidents [25]. However, all these ontologies do not use service reports. Therefore, within the project "ReStroK" a new ontology was developed based on the evaluation of service reports that establishes a connection between the formal turbine structure, status data and free texts and the experience knowledge of the service technicians [11]. This ontology represents an important basis for the prescription of maintenance activities of onshore WTs and the necessary identification of damage mechanisms as well as corresponding maintenance measures.

3. Development of a prescriptive maintenance approach for onshore wind turbines

The access to asset data, including unstructured data from service reports is a prerequisite for the realization of a prescriptive maintenance approach [17]. However, especially SMEs often do not have access to such data. Thus, an ontology can be used to make such data accessible and usable [11]. Based on this ontology a prescriptive approach was developed as a part of the “ReStroK” research project to realize a prescriptive maintenance strategy. The main steps in the developed approach are the definition of a scope, the set-up of prescriptive maintenance steering and control, utilizing a previously developed ontology and the development of the function tree as well as the measure catalogue. The structure of the developed prescriptive maintenance approach is shown below in Figure 3.

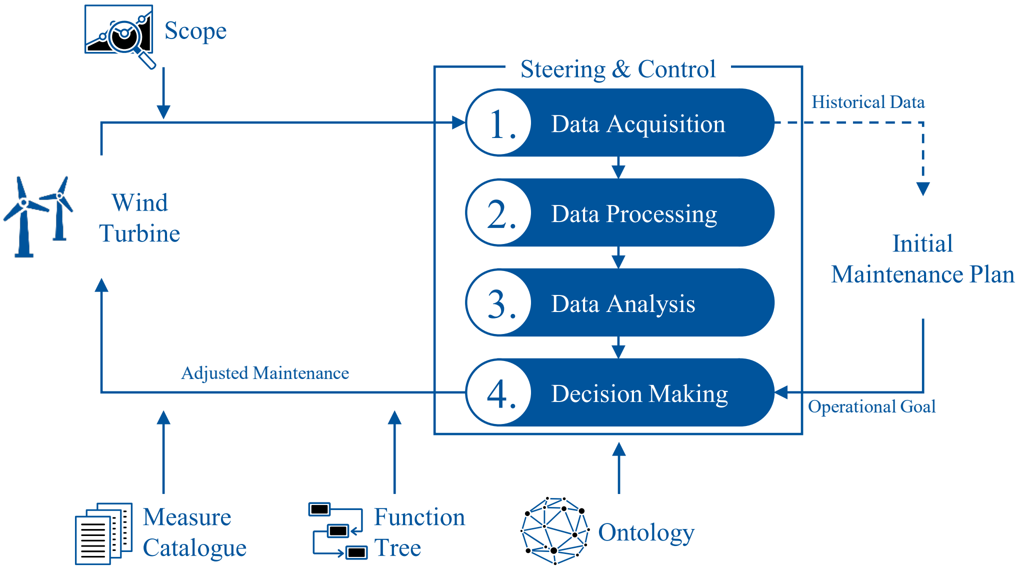

Figure 3: Prescriptive maintenance approach framework (Source: own representation)

3.1 Scope

While the overall functionality of onshore WTs does not differ greatly between manufacturers, the same cannot be said for their structure and subsystems. However after an analysis of the maintenance history of the WTs under consideration it was found that roughly 80% of the failures could be traced back to the pitch and to the converter system. Considering the time and capacity restrictions of the research project it was decided to put the initial scope for this work on the pitch and converter system.

3.2 Ontology to enable maintenance steering and control

As shown in Figure 3, data is needed to initiate the correct maintenance activities and control their effect. Concurrently it is used to make adjustments when needed. Especially unstructured knowledge from maintenance and service reports offers valuable insights into the state of WTs as well as the effect of conducted maintenance activities. Strack, Lenart et. al. developed an ontology, specifically tailored to onshore WTs, to link the implicit knowledge of service technicians with the operating and master data of

WTs and to enable the automated evaluation of service reports regarding fault findings and the evaluation of effects [11]. The developed ontology enables the incorporation of the unstructured knowledge found in service and maintenance reports for maintenance activities. This is made possible by linking error codes and maintenance reports. In the process of developing the ontology, the relevant terms were identified using text processing. This resulted in a database of terms and term frequencies, which were filtered in the next step. Finally, the terms were clustered and relations were defined to formalize the ontology. By using this ontology for this project, it is possible to automatically evaluate existing maintenance and service reports for issues and potential future breakdowns and trigger maintenance activities. It also enables the subsequent evaluation of conducted maintenance and service activities by enabling an algorithm to scan reports (incl. free text fields) for key words which correspond to indicators for the success or failure of conducted activities.

3.3 Function tree

In literature, many characterizations of the term "prescriptive maintenance" and the structure of the corresponding activities are described, however the realization remains fuzzy. Only few sources go beyond simply pointing out the need for a "set of tasks" and these are not specific to onshore WTs [17,26]. So for this project a measure catalogue needed to be developed.

In order to develop a measure catalogue, a function tree is required to properly link recognized errors (e.g. from error messages) with faults in specific components. A function tree also extends to the sensor layer and their connections as an error can become observable on a level other than the underlying root cause. This is caused by the sensor setup in a WT. Thus, the function tree also enables the analysis of error codes regarding the "triggering" component [11]. An example would be the following error message: Error pitch system [Angle error blade A/B/C]. This can be assigned to the position sensor or the pitch motor in the function tree, for example. For this work, a function tree was developed in expert interviews with domain experts (such as wind farm operators or WT service engineers). The initial focus of the development was put on GE turbines (making up the majority of WTs in the wind farms under consideration), however the function trees can be expanded to WTs by other manufacturers in the future. As described above, the focus for the function tree was put on the pitch and converter system. In this function tree these systems and their sub-systems were structured. An extract is shown in Figure 4.

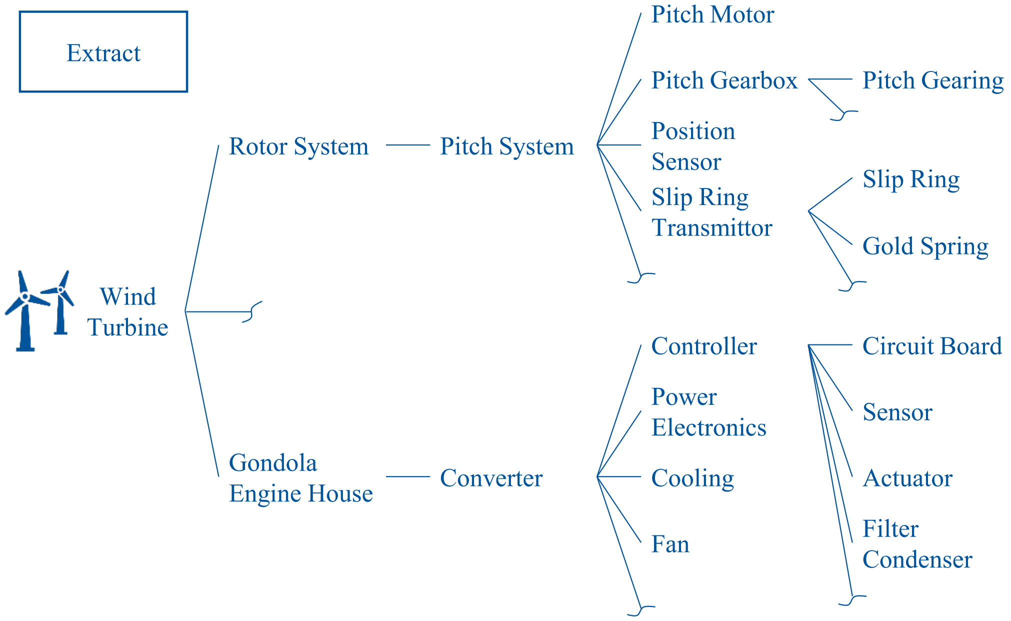

Figure 4: Function tree - pitch system and converter (Source: own representation)

3.4 Measure catalogue

Based on the developed function tree, interviews with domain experts to determine and validate specific actions for specific breakdowns on a component level were conducted. An initial set of maintenance measures was collected utilizing literature research and expert interviews. This set of measures was discussed, validated and extended. These measures are collected in the measure catalogue structured as shown in Table 1. When a certain error is recognized, a list of measures, which typically resolve the identified error is suggested to the maintenance technician.

Table 1: Excerpt from the developed measure catalogue (Source: own representation)

Category	Damage Mechanism	Maintenance Measure
Pitch system	Faulty battery	Change pitch battery
Pitch system	Position data outside tolerance	Check position sensor
Converter	Faulty converter controller	Check corresponding sensors, actuators and circuit board

The measures are currently mostly specific to GE WTs, but with moderate translation effort these can be applied to turbines of other makers as well. In addition to the expansion, an algorithm needs to be developed to connect the ontology with the measure catalogue to enable the automation of the prescriptive maintenance approach.

4. Summary and outlook

Wind power is a pillar of the renewable energy mix. The O&M costs for onshore wind turbines are a major addressable cost driver. The use of a prescriptive maintenance approach is a possibility to drive O&M costs down. A prescriptive maintenance approach utilizes insights from data analytics to derive maintenance activities and considers the object of maintenance activities to be a guiding and controlling element. However it heavily relies on (unstructured) data to be effective. An ontology can be used to make vast amounts of unstructured data (such as data from service reports) usable for such an approach, thus enabling SMEs without an abundancy of resources to pursue such approach.

This work demonstrated how this unstructured data can be used to carry out a prescriptive maintenance approach. First, based on an ontology, which enables automated analysis of event data of WTs, a function tree was developed to link errors with the underlying root-cause. Following this, measures to counter specific issues in specific components of WT systems and sub-systems were developed in close collaboration with domain experts. Then, these measures were collected in a measure catalogue, to provide maintenance and service technicians with the means to counter damage mechanisms with specific maintenance measures. The collection of measures and validation is ongoing. In a next step, the list of measures needs to be expanded, as the initial focus was only put on the pitch system and converter. Thus enabling a prescriptive maintenance approach, increasing maintenance effectiveness and lowering O&M costs.

In the next step, this measure catalogue needs to be expanded to other WT systems and WT manufacturers. In a further step an algorithm to identify relevant events in historical service reports will be developed. This algorithm will also provide users with an appropriate interface to fully realize the potentials of the developed approach. Also, further research with focus on monetary effects of the prescriptive maintenance approach and the corresponding maintenance activities is recommended to improve transparency of the return on maintenance (similar to the return on invest). This will allow for an improved and more holistic maintenance understanding and will unlock the potentials of a modern maintenance organization.

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Biography

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Florian Pfau pursues his master's degree (M.Sc.) in Business Administration and Mechanical Engineering at RWTH Aachen University. He has been working at the Institute for Industrial Management (FIR) since 2020 as a research assistant with focus on maintenance operations and wind power, particularly in the ReStroK research project.