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Through-life engineering services of wind turbines[☆]

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ABSTRACT

The past decade has seen exponential yearly growth in installed capacity wind energy power generation. As a result, wind farm (WF) projects have evolved from small scale isolated installations into complex utility scale power generation systems comprising of arrays of large wind turbines (WTs), which are designed to operate in harsh environments. However, this has increased the need for through-life engineering service (TES) for WTs especially in offshore applications, where the operations and maintenance (O&M) becomes more complicated as a result of the harsh marine weather and environmental conditions. In this paper, a generic methodology to benchmark TES in industries is presented and used to assess TES in the wind industry. This was done by identifying the current state-of-the-art in methods and applications, requirements and needs, challenges, and opportunities of TES in the wind sector. Furthermore an illustrative case study on WT gearbox through-life support is presented demonstrating how some of the core aspects, such as remote condition monitoring, can be used to aid the in-service support of wind turbine gearboxes.

Introduction

Renewable and alternative energy technologies have developed from very small scale R&D projects to commercial technologies, contributing to the global energy and power generation mix [1]. Of significance is the power generation from wind energy which is now a very popular source of clean energy, having had an exponential growth in the last two decades (see Fig. 1) and currently generating about 2.5% of global electricity supply [2]. This growth has been forecasted to continue, as the amount of global electricity that could be supplied by wind in 2020 is estimated to be between 8 and 12% [2].

As the typical WT is designed for at least a 20 year life time, there is an essential need for through-life support in order to sustain the continuous operation of the WTs at a minimum life-cycle cost. However, designing, delivering and most especially, supporting WTs are not without challenges, one of which is as a result of the nature of their operating environments (offshore locations in particular). Also, as governments reduce or pull out from subsidies and tax credits, the industry is faced with a challenge of cost reduction (both on the product design and manufacture, and the O&M costs) so as to be as competitive as the conventional and nuclear power sectors with relatively low cost of energy.

This paper is in two parts: the first half explores the original topic of TES in the wind industry, presented by the authors in an earlier publication [1], by identifying the state-of-the-art and current challenges of TES in the wind industry. Also, a forward looking perspective is taken by identifying possible opportunities which could address the challenges and meet future TES needs and requirements in the industry. The second half presents a case study on WT gearbox through-life support, which takes further previous work by the authors (see [1]) by going through the key steps of identifying the TES requirements and needs and its implementation. A focus will be placed on how TES can be applied to offshore WFs since the impacts of poorly understood and executed in-service phase on O&M costs are far greater in offshore applications, and furthermore offshore wind is still in its nascent stages [4].

The main contributions of this paper is as follows:

- This paper closes the gaps in literature in the topic of TES in the wind industry. As at the time of writing this paper, there was little literature in the research domain that dealt with the topic which is of importance for the wind industry.

[☆] An earlier version of this paper was presented at the Third International Conference on Through-Life Engineering Services in 2014 held on 4–5 November 2014 at Cranfield University in UK.

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Nomenclature

CBM	condition based maintenance
CM	condition monitoring
CMS	condition monitoring systems
KPIs	key performance indicators
MRO	maintenance repair and overhaul
OEM	original equipment manufacturer
O&M	operations & maintenance
PD	product development
PSS	product service systems
SCADA	supervisory control and data acquisition
TES	through-life engineering services
WF	wind farm
WT	wind turbine

- This paper also proposes an approach for benchmarking TES presented as a methodology (identifying the current state – defining the requirements and needs – identifying challenges – designing implementation) which can be easily applied to other industries that looking to explore the adoption of TES.
- A case study on WT gearbox TES which identifies and addresses salient issues being faced in the offshore wind industry was also presented. One particular issue dealt with in this paper is the use of remote monitoring as a key enabler for the continuous learning and optimisation of WTs in a TES context.

Theoretical background

Related works

For many long-lived complex engineering artefacts, such as aircrafts, ships, naval vessels, conventional and nuclear power systems, to name a few, there is a great emphasis on TES, right from the early PD stages through utilisation and until retirement. This is partly because of their complex design, but also because they are expensive to manufacture and maintain. Furthermore, these kinds of artefacts need continuous support since they are typically in operation for decades. This means that the majority of the life cycle costs are attributed to the in-service phase of these systems, with maintenance costs often exceeding the initial capital cost over the life time of the artefact [5]. Modern WTs used in most WF projects have close similarities to these kinds of artefacts in many of these aspects. First, WTs are designed to be in service 20 years or more, during which the WTs are expected to keep operating as long as the wind blows. Second, due to the complexity in design and the nature of their operations, WTs require adequate support during in-service especially for the offshore types. Hence a similar emphasis on TES is also required by companies who make, operate and maintain WTs in order to deliver the necessary through-life support for WFs.

According to literature [1,6–8], TES involves the managing products and services which are needed in order to deliver a fully integrated capability (product, its functionality and required support) to the customer. This process of integrating of products and services implies that OEMs now have more responsibility for the entire life cycle of a product and are not just responsible for making a product and selling service and support offerings to customers as add-ons [7,9]. As a result, there is now a reduction in the ownership costs of a product for the customer [6], i.e. customers do not necessarily own the product but pay for the capabilities it provides [10]. Another dimension of TES is that it presents OEMs with the opportunity of learning about product usage by customers [7], since they have access to product in-service data. Hence, this gives them a broader scope and motivation to learn from their involvement in in-service activities and use this knowledge for product improvements via redesign and upgrades [1,10]. Perhaps the most important aspect of TES is that it provides OEMS with a means to ensure that the required product value is realised by the customer over all stages of the life-cycle. Value may be a combination of services or promised function, capability or availability.

Relevant to the scope of this research article, antecedent literature have researched into identifying and understanding the challenges and opportunities of TES in different sectors such as Nuclear [11], Maritime [12] and Automotive [13]. For example, Norden et al. [12] proposed a new service contract business model for through-life asset management in the maritime industry. This model provides a holistic service package which is customisable and offered for a fixed time based fee. Knowles [13] discussed the through-life management of electric vehicles, identifying the role which TES has played in addressing the issues with electric vehicles' technologies, and recommending directions for future research. More closely related to the support WTs are the works by Tracht et al. in [14,15], where they deal with an aspect of TES of offshore WTs by developing models for accurate spare parts demand forecasts.

On a methodology for benchmarking TES

When the authors of this paper ventured on the quest of exploring the potential applying TES in the wind industry two

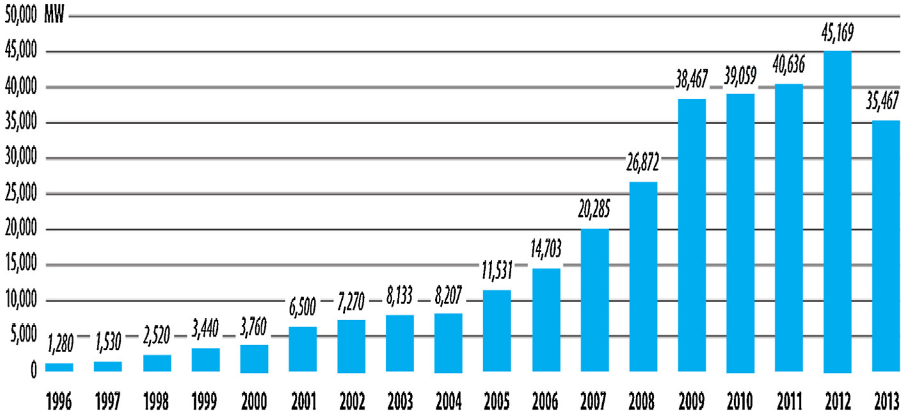

Fig. 1. Global annual installed wind capacity [3].

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major obstacles were met. First, there was a lack of literature in the application of TES in WTs. This was perhaps due the fact that the wind industry is still young compared to others such as aerospace, automotive and nuclear, and hence most of the research in the WT domain have focused on dealing with many of the challenges WTs face as a modern technology – such as reliability and maintenance, standardisation across the industry and dealing with supply chain and logistical issues. There is also the possibility of the lack of research in this area being linked to the lack of demand by the industry due to a focus only on the main challenges. However, it will be shown that these key issues are at the heart of TES and can be harmonised into a unified approach that focus on delivering value through the life of a WT. Second, there was little in the public domain about how a company, industry or sector which is immature in TES can benchmark and design an appropriate implementation plan for delivering TES in their industry. For example, the likes of [11–13] mentioned earlier have only focused on identifying challenges and new opportunities and business models when applying TES in their respective sectors. Although, the authors acknowledge the works of the likes of [5,7,9,16,17] who have dealt with the design of functional or total care products and the services which need to be delivered whist these products are operational. However, these have largely focused on the designing, developing and delivering of product services. This paper builds on these works by proposing a methodology for benchmarking TES based on the best practices of service design and delivery in manufacturing organisations together with a detailed identification of the challenges identified in literature. This benchmarking process is in three stages – initial assessment, TES design and delivery (see Fig. 2).

The benchmarking process begins with an initial assessment which entails the identification of the current state-of-the-art in TES for the industry in question. These include all the current best practices for through-life support. The following checklist of items need to be addressed fully in order to benchmark the current best practices of TES in any industry:

- Identifying the nature of the product life cycle.
- Defining the types of stakeholders involved in delivering the life cycle.
- Identifying the types of through-life support contracts, i.e. the relationships between OEMs and customers for service and support during the operation of the product.
- The state-of-the-art in MRO procedures.

The aspect of TES design has been covered in detail by [5,7,9,16,17], however two key aspects that must be addressed during the benchmarking process are the definition of TES requirements and needs, and the challenges and opportunities for meeting these requirements. Following these will then be the delivery stage, which includes the process of defining action plans for the implementation of TES and identification of metrics which can be used to measure the outcomes against the TES requirements.

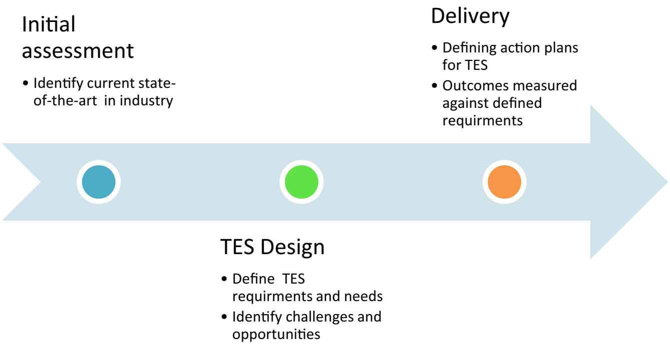

Fig. 2. Methodology for benchmarking TES.

In the next section, the three stage methodology presented above is applied to benchmark TES of offshore WTs.

Wind turbine through-life support

In this section, an attempt would be made to use the methodology proposed in the previous section to benchmark TES application for WTs. The aim is to shed some light to the current best practices, short comings and future opportunities for adopting TES in the wind industry.

Current state-of-the-art in TES

Life cycle management*:* A typical WF has a life cycle described by the following key stages (see Fig. 3): WF site planning & design, turbine (system) specification, subsystem & component design-integration-validation, turbine integration, validation, installation & commissioning, utilisation & support and disposal. Of all of these, there is a keen interest by WT OEMs in managing and delivering the utilisation & support stage. This is because WTs have very high O&M costs of WTs, which have been very difficult to predict upfront by OEMs during the planning and design phase [18]. This high cost has been driven by a historically high amount of unscheduled maintenance of WTs which resulted from high amounts of early failures in WTs [19,20]. This uncertainty in O&M cost estimation shows the need for TES so that OEMs can learn from WT operation to improve product design and performance.

TES stakeholders and contract types: In general, a typical WF project will consists of several stakeholders ranging from the developers, financers, utilities, WF owners, OEMs, suppliers, governments, communities and even the environment [21]. With respect to the types through-life contracts, the relationships of importance after a WF project has been given a go ahead (i.e. from PD until utilisation and support), are those between the OEMs, customers (WF owners and/or financers/developers), and suppliers. The kinds of through-life contracts between these stakeholders vary from long term full service and performance contracts to basic product warranty type contracts. Depending on the type of contracts OEMs have with their customers, MRO activities can be either carried out by the WT OEMs [22], by the customers (for owners of large WFs who their own service personnel) or by third-parties or independent service providers. In the latter two cases, the customers or third party service providers purchase component spares from OEMs. These contract types are unlike the typical performance or availability type contracts which are the current state-of-the-art in industries such as aircraft and nuclear. Although, there are a few of the WT OEMs who currently offer some form of performance based contracts to their customers, their application in the wind industry is still immature [1].

State-of-the-art in O&M: Preventive maintenance and reliability centred maintenance have until recently, been best practice for O&M in the wind industry [22,23]. However, there has been a gradual shift towards CBM for multi-megawatt WTs after series of catastrophic failures of main components in the early 1990s [24]. In addition to that, WTs in offshore or remote locations are installed with remote monitoring due to the difficulty to access the sites and the enormous cost associated with regular visits to

Fig. 3. Life cycle of a typical WF project.

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the WFs. This can be achieved by the installation of sensors for CM of WT components which measure key parameters of the WT that can give an indication of deterioration in component health. Measuring WT health enables the identification of potential defects and abnormal operations which in turn facilitates the proactive planning MRO activities well before failure occurs, hence reducing downtime due to unscheduled service and ensuring that performance obligations are met [20,25]. For more details on the current best practices in WT monitoring see [24,26–30].

TES requirements and needs

The fundamental customer requirement of WTs is the ability to generate electricity from wind energy as long as the wind blows (within specified design and operational limits). In addition to this there are other factors which influence design and operational requirements. For example, many WTs are designed for use in locations with harsh and unpredictable conditions and complex terrains. This is because the best and consistent wind resource is abundant in such locations, for examples in mountainous terrains or offshore deep water sites. This by its very nature comes with challenges not only in the difficulty in estimating design and environmental loads but also during the utilisation stages of the life-cycle due to the remoteness of the sites. On the one hand, the underestimation of operating loads have previously resulted to early failures of WT components e.g. gearboxes [19,31,32]. On the other hand, even as these operational loads get better understood (as a result of several decades of experience by OEMs) and accounted for in the design, there are still challenges faced during O&M of WTs, one key example of this is the issue of site due to harsh environmental conditions (especially in offshore WFs). This in turn leads to longer downtimes and high O&M costs [18,33].

Taking a through-life view, it is important for OEMs to be able to design, deliver and support WTs, not just to be able to withstand the harsh operational environment, but also to do this as the lowest through-life cost. Therefore for proper implementation of TES, WT OEMs have to ensure that WTs are designed to meet these requirements. Furthermore, the customer also expects the capabilities of WTs to be delivered at the lowest O&M cost throughout the lifetime of the WF. In order to meet these requirements, especially within the context of a performance or availability based contract, OEMs need to account for the following TES requirements [1]:

- system and component failure modes, failure rates and degradation patterns for reliability estimation, useful life prediction and maintenance optimisation;
- a robust logistics and supply chain structure that incorporates the use of predictive models which can account for the uncertainties that result from weather and environmental factors;
- an adequate training to service personnel for more efficient and effective maintenance task delivery; and
- the availability of equipment, tooling and technology needed for improved maintainability and supportability.

TES challenges

Environment and operating conditions

Sufficient evidence exists in literature which suggest that the major TES challenges faced in WF context are related to the environmental and operational conditions [19,31,32]. As explained earlier, these challenges can impose constraints on how OEMs manage all life cycle stages. First, WTs constantly exposed to extreme and fluctuating loading conditions, which had led to a difficulty in estimating design loads in the past [19,31]. Second, harsh weather, complex terrains and changeable environmental conditions impact the scheduling O&M for WFs. This is a much bigger issue in offshore WFs where sea conditions can be very extreme making it difficult or almost impossible to gain access to WFs at certain times of the year. For example, many offshore WFs have been previously known to experience months with over 20 unworkable days due to extreme conditions [30]. The implication is that O&M tasks must be carried out only during accessible seasons. Here, components which are likely to fail during unworkable days are repaired or replaced proactively [24]. This requires extensive prediction and planning, and in practice is very difficult to achieve because a wrong decision or timing could result in a significant economic loss [24].

Technical challenges

In addition to the challenges linked to WT operating conditions, there are other technical challenges which influence the implementation of TES in the wind industry. One very good example is which is faced in the CM of WTs (see Yang et al. [24] for a more detailed overview). The issue faced by WTs during CM is that unlike a typical conventional rotating machine,[1] the relationships (i.e. the physics) between WT CM signals, such as vibration and temperature, and component integrity is not straight forward, i.e. they are sensitive to many other factors such as the variability in operating conditions [24]. Hence, sudden increases in vibration and temperature levels of WT component might not necessarily imply a fault [24], which makes it very difficult to detect and/or predict the incipient faults using conventional CM algorithms. The authors have already began looking into ways in which such parameters (e.g. gearbox vibrations) and be monitored using new data driven approaches (see [20,29]). Moreover, other researchers including [34,35] have explored different approaches for modelling WT operational behaviour.

Another challenge, perhaps not very apparent, is the immaturity in the application of prognostics and diagnostics technologies specific to WT use. Antecedent literature [23,24] show that only a few CM techniques such as vibration analysis, oil particulate analysis, and fibre optic strain gauges are available for commercial use in WTs applications. Moreover, these technologies are only typically used for online monitoring and not for full fault diagnosis. Other technologies such as ultrasonic NDT, thermography, and acoustic emission transducers, which are normally used for detecting cracks and structural degradation in many other industries, either do not have competitive/commercial WT applications yet or are still only used for research and testing purposes [24]. This immaturity limits the scope and ability to apply integrated health monitoring systems commercially for WTs.

Finally, there is a challenge in developing required infrastructure, e.g. harbours, onsite component storage and ships, needed to support TES activities in offshore wind, adding another dimension of complexity to WF projects.

Opportunities for TES

The above mentioned challenges give rise to opportunities (business and technical) for TES in WTs.

Business opportunities

The main opportunity for WT OEMs in TES is that attributed to the shift from traditional product offerings of just selling WTs to customers and WF developers to an integrated PSS, where the WT OEMs provide wind power plant solutions. This type of business

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[1] Most rotating machines and reciprocating engines which have a gearbox are conventional in the sense that the gearbox is used to reduce the engine speed. A WT is unconventional because its gearbox increases the speed of the rotor blade at a very high torque in order drive the generator at higher RPMs.

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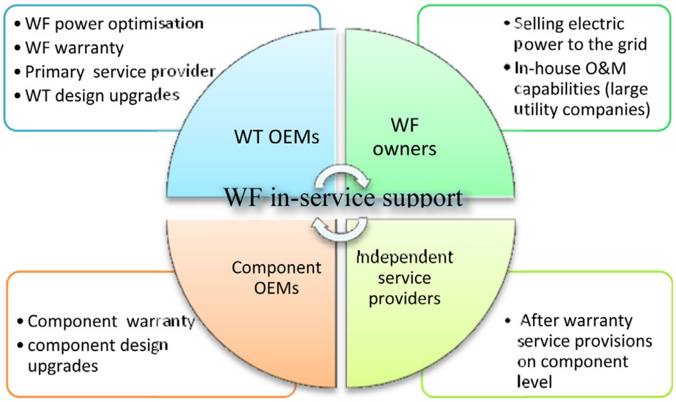

Fig. 4. Stakeholders in WF in-service support [1].

model requires through-life competencies and expertise (e.g. repair, overhaul, performance upgrades of WTs and other aftermarket services) from WT OEMs, and not just expertise in PD, so as to meet the fundamental TES requirement. However, this is not a straight forward task as there are a number of competing forces involved in delivering TES. Fig. 4 illustrates this, presenting the key stakeholders involved in a WF in-service support. It can be seen that there is a scope for large WF owners (who have prior experience with conventional power plants) to have in-house O&M capabilities, and also to contract O&M to third party independent service providers. Hence for WT and component OEMs to adopt a TES type business model, they have to introduce the PSS design upfront in early PD.

Technical and research opportunities

It clear that in the process of benchmarking TES there are identifiable technical and research opportunities which can be able to address the previously discussed challenges of TES in WTs. Specific to these challenges are some areas which are yet to be explored either by WT research or in commercial WT applications are: (i) the use of self-healing technologies, (ii) application of integrated monitoring systems and (iii) exploring the adoption of autonomous maintenance for WTs. Self-healing technologies can significantly have a positive impact in the robustness and resilience of WT systems, hence reducing downtime, by being able to reconfigure their architecture to ensure that their operation when failure occurs. This application can be used to address electronics and control software failures in WTs. Second, having an integrated health monitoring system which combines multiple CM and detection technologies/algorithms improves the detectability and prediction accuracy of WT faults. Research can look into health monitoring techniques, such as thermography, acoustic emissions, etc. for WTs. These technologies have the ability to complement already established vibration and oil CM which could lead to a possibility of combining all these technologies into a full integrated health monitoring system for WTs. Finally, Autonomous maintenance can play a huge role in WT inspections where access to WFs is hampered by harsh conditions. The use of new robotics technologies such as drones, humanoid robots for inspections can be explored for making video inspections (and non-destructive inspections), which can be streamed to maintenance personal remote operational centres.

Case study – WT gearbox TES

Background

Gearboxes are one of the most expensive subassemblies of a WT due to their high manufacturing costs and also because they are the most expensive to replace [32]. The high replacement cost is largely due to the complexities in maintenance and repair procedures of gearboxes – especially in offshore applications [26]. Furthermore, many gearbox repair solutions require the use of heavy lifting equipment and tooling such as external cranes and vessels (in offshore WFs) for dismantling and transporting parts. These tools required for gearbox O&M are expensive to procure and maintain for use in WFs. In addition to the cost of O&M, gearboxes have been known to have a high failure rates resulting from design defects and underestimation of operating loads [19,32]. Also, compared to other WT subassemblies, gearboxes have a higher downtime per failure [36–38]. These historical issues make WT gearboxes ideal candidates for a case study which illustrates how WT TES can be implemented. This case study takes an approach if drawing from key lessons and experience of WT gearbox O&M from both academic literature and industrial experience. As much of the TES challenges of WTs are equally faced by their gearboxes, this case study will only touch on the TES requirement and how they can be implemented in practice.

TES requirements

Just as for the overall WF, the fundamental TES requirements for WT gearboxes are that of availability (ability to transmit wind kinetic energy towards generating electric power, as long as the wind blows within design limits) and O&M costs. However, this can be broken down into two measures of technical and operational effectiveness.

Technical effectiveness

The requirement of technical effectiveness is very important because from the OEMs point of view, the functionality or promised availability of a WF is perhaps the key selling point to their customers. Hence, for technical effectiveness to be achieved, the minimum requirements of functionality and availability have to be met, see Fig. 5.

The primary function of the gearbox is to transmit power from the rotor to the generator. To fulfil this requirement, the gearbox must be able to [39]:

- Increase the low speed from the rotor to the high speed of the generator, while compensating for the torque differences across the gearbox resulting from variations in speed.
- Remain functional for 20 years under dedicated and acceptable maintenance.

Most of the functions and design attributes are defined in the system design phase of the gearbox life cycle. However, field performance which is linked to functionability can be measured

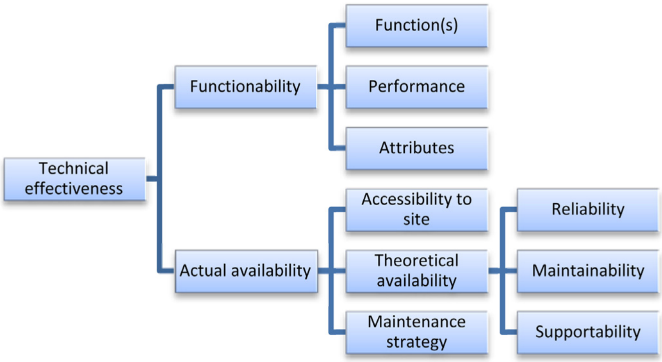

Fig. 5. Technical effectiveness for WT gearbox TES, adapted from [40,41].

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and benchmarked against the design requirements. For example, the power output to the grid can be measured and compared with the theoretical power curve to ensure that the WT is producing power within the set limits under set conditions. The relationship which can be used to measure the gearbox performance is the amount of kinetic energy transmitted by the gearbox. This can be calculated as follows [26]:

$$E = \frac{1}{2} I_{gbx} \omega_{gbx}^2 \eta_{gdx} \approx P_{gen} T \tag{1}$$

where I_{gbx} is the moment of inertia of the gearbox; ω_{gbx} and η_{gbx} are input speed to the gearbox (rotor speed) and the gearbox efficiency respectively; while P_{gen} and T are the generator power output and the time interval when the measurement is taken respectively.

From the power production perspective, the WT availability is of great importance, which is directly impacted by the availability of the gearbox. The availability of a WT is the percentage of time it is able to produce electricity whilst the wind is blowing within a defined operational window [40]. This is a function of the reliability, maintainability and supportability of the WT [41]. This measure of availability applies to all other WT main components including the gearbox. It has been identified that one of the main challenges faced by WTs is the issue of accessibility to WFs. This issue plays a central role in determining the actual availability since weather conditions can affect response of service personnel to resolve downtime issues. Therefore the actual availability has to consist of the theoretical availability, ease of accessibility to WFs for O&M tasks and the type of maintenance strategy adopted by O&M managers. Hence predictive models for site access using operational, environmental and weather-related data have to be integrated to traditional maintenance models in order to ensure that availability targets are met. Therefore, the WT availability can be estimated from Eq. (2).

$$A = \frac{Uptime}{Uptime + Downtime} \cong \frac{MTTF}{MTTF + MTTR} \tag{2}$$

where $MTTF$ and $MTTR$ are the mean times to failure and restoration respectively. In practice, the downtime and $MTTR$ will compose of the supply chain, weather and logistical factors which influence the actual availability. The difficulty is not in measuring these values from historical data but rather in predicting them with accurate models. Apart from the impact of site accessibility on the availability, the maintenance strategy also plays a major role in the overall availability of the WT gearbox. As mentioned earlier, RCM is the current best practice for WT operators. Owner, in offshore applications, CBM is used as the primary maintenance strategy by remote monitoring of gearbox sub-components. In addition to that, and in some other applications such as for onshore WTs operators are faced with a choice between several maintenance policies within the RCM strategy. In [25] a detailed analysis was made for how such a choice between a preventive and corrective maintenance policy can be made for WT gearboxes. The inequality expressed below has to be satisfied for a preventive maintenance policy to be economically feasible, otherwise it would rather be cheaper to adopt a corrective approach or CBM (if possible).

$$\frac{F(FMT^p) + (CMT^p/CMT^c)}{FMT^p} \ll \frac{1}{MTBF} \tag{3}$$

where FMT^p is the interval between scheduled maintenance; $F(FMT^p)$ is the probability of failure occurring before scheduled maintenance; CMT^p and CMT^c are the respective preventive and corrective maintenance costs per activity; and $MTBF$ is the mean time between consecutive failures.

In summary, achieving technical effectiveness requires a lot of focus in defining and understanding the system performance requirements as early as possible during the PD phase. If such requirements are not well understood, it could result in a reduction in performance, i.e. reliability and maintainability. As mentioned earlier, there is evidence of this in the wind industry where early WT gearbox design loads were underestimated, leading to higher than expected failure rates and hence resulting in lost revenue due to high O&M costs attributed to downtime from such failures [19,31,42].

Organisational and operational effectiveness

Whilst the technical effectiveness can be easily quantified and measured, assessing the organisational and operational effectiveness requires a more qualitative approach. This is because it is not particularly straightforward to define quantitative measures for organisational and operational effectiveness. However, there are well-known metrics which organisations use to measure business performance. For example Kaplan et al. [43] introduced the balanced scorecard which is used by many organisations for measuring business strategy from the financial, customer, business process and growth perspective. The authors find this approach as a useful way for organisations to define their TES organisational and operational KPIs and link these to the wide business strategy. Some of such KPIs include [44]:

- quality;
- delivery reliability (e.g. lead times, response times);
- customer satisfaction;
- costs;
- safety; and
- morale.

In addition to these, there are other key constituents of organisational and operational effectiveness which are necessary for driving the implementation of TES in an organisation. Some examples of these include:

- Having a clearly defined strategy for TES.
- Recruiting individuals with the right set of skills, expertise and competencies.
- Leveraging systems and technologies, such as advance IT systems and Big Data solutions, which would automate and support TES related processes.

Implementing TES

The authors have, decided to focus on two aspects of TES implementation in this case study due to the scope of this paper. These are (i) the importance of remote monitoring, and (ii) the continuous learning and optimisation process of TES.

Remote monitoring

It is now clear that using the state-of-the-art in remote online monitoring during the utilisation and support phase, can help in achieving TES technical effectiveness. CMS is used for detecting and diagnosing incipient failures in a WT gearbox. Also SCADA systems can be used to trend operational/environmental data with O&M records in a WF. The trends that are obtained can be used to monitor the operational performance of gearboxes. Both systems (CMS and SCADA), if used properly, can provide timely warning to of an impending fault to WF O&M managers in the form of alarms. Therefore, O&M managers have sufficient time to plan or schedule maintenance tasks hence being able to take advantage of favourable weather conditions when they arise.

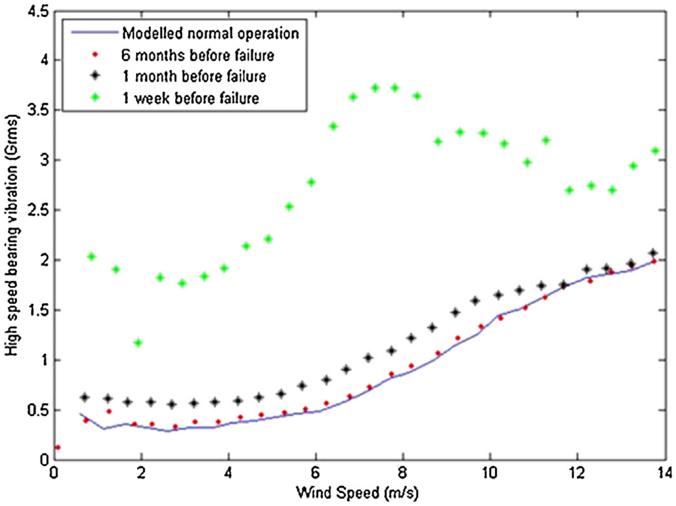

Fig. 6. WT gearbox high speed bearing vibration remote monitoring [20].

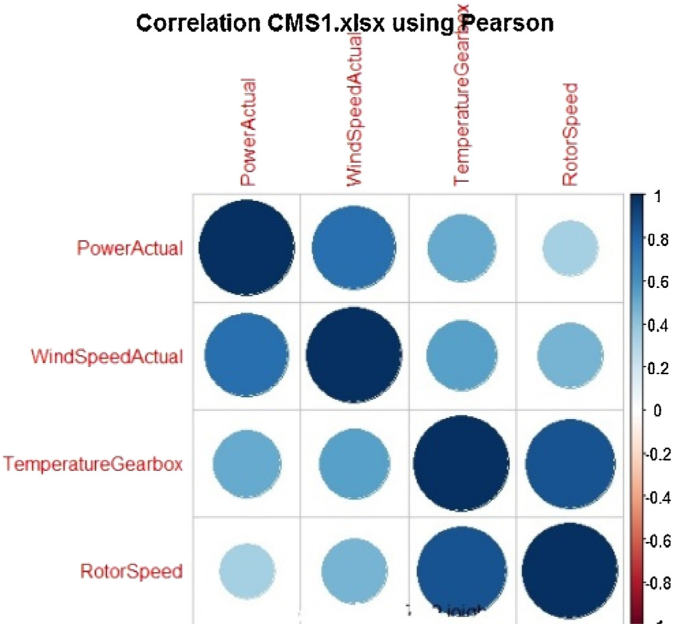

Fig. 7. Correlations between input variables for data model.

Fig. 6 shows an example of a WT gearbox high speed bearing vibration remote monitoring via CMS done by the authors in [20,29]. Here, the relationships between the wind speed and RMS values of the vibration signals have been modelled for normal operation (see [34] for more on the modelling approach). The vibrations for subsequent intervals can then be correlated with this to detect the development of a fault. From Fig. 6, it can be seen that the indication of failure comes as early as 1 month. This buys time for the WF operator in planning for O&M both in responding to the demand for resources and spare parts but also in dealing with the challenges of accessibility to the WF and other logistical issues as well.

The above monitoring method relies on the ability of a data analyst to model the normal operation and use this to detect miscorrelations from data of different operating windows. This means that the downside of this method is that it is very difficult to measure what degree of miscorrelation corresponds to failure, without using a graphical method (although [29,34] have both successfully measured this miscorrelation analytically). Hence, in order to have an automated detection approach that can be programmed into the wind turbine controller and CMS system to trigger automatic alarms, alarm levels can be designed by using machine learning and other data mining techniques to develop normal operating models which are used to obtain the correct trigger levels. Such models for example, artificial neural networks (ANN), random forest and logistic regression models, can be developed using operational parameters such as wind speed, rotor speed, temperature and response parameters such as gearbox temperature, pressure, power output, etc., to determine the normal operating model that defines the behaviour of each wind turbine gearbox.

For example, the same vibration data used for the graphical prediction in Fig. 5 has been modelled using three of the algorithms mentioned above for the purpose of this case study. As usual, the modelling process used the normal operating condition for training, testing and validation of the respective models, while the detection and trigger levels where determined by a rule-based approach using the operating window from a period of 6 months before failure. Fig. 7 shows an example of initial data summary which looks at the correlation of some of the input variables used for predicting the normal operating vibration (at respective values of these input variables). It can be seen that there are some very strong positive correlations between some input variables such as rotor speed vs. gearbox temperature and wind speed vs. power output. This should indicate that an increase in vibration might be explained by a combination of multiple factors[2] and unlike in Fig. 6, where the correlation between vibration and wind speed has been used to develop the normal operating behaviour, a model that combines all these variables will be used instead.

There are many commercial software packages that can develop data models from numeric data. The authors have made used of the statistical programming software called “R” for developing the models. Fig. 8(a)–(c) shows the respective results of the validated models (predicted vs. observed vibration values) which was obtained after modelling the data with the three methods mentioned earlier.

From Fig. 8 it can be seen that all three models accurately predict the bearing vibrations during normal operation. This implies that the normal model can be used do define trigger/alert levels for predicting failures (deviations) and abnormal behaviour. The authors proposed a normalised approach for developing the trigger level given by the equation below:

$$Dev_i = 100\%\times\frac{obsv_i - pred_i}{MAX\left(\sum_{i=1}^{i+360} pred_i\right)} \tag{4}$$

where *obsv* and *pred* are the respective observed and predicted vibrations and i is the time stamp. The denominator uses a summation of $i = 1$ to $i = i + 360$ because the data used in this case was 2 min data which means that there are 360 data points in a day. Therefore the denominator is the same as the daily maximum predicted vibration. This means that the lag of detection using this approach is shortened considerably to

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[2] It has been mentioned in the previous section that the increase of decrease in temperature or vibration might not necessarily mean the presence of a fault, and depends on many other input variables. Therefore the use of multiple input variables ensures that normal operation models are developed with enough robustness eliminating potential noise and false indications of abnormal operating conditions.

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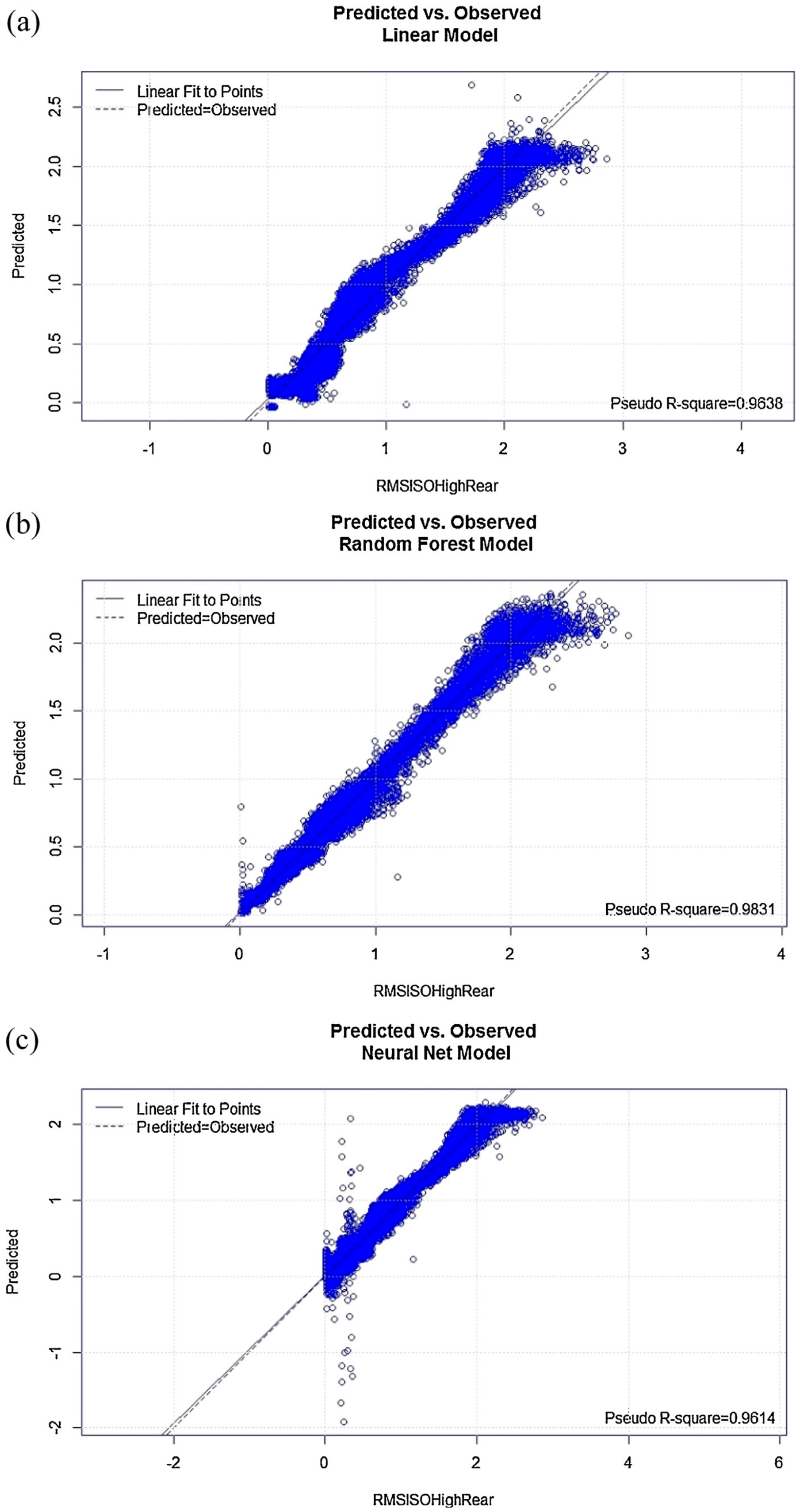

Fig. 8. Predicted vs. observed gearbox high speed bearing RMS vibrations.

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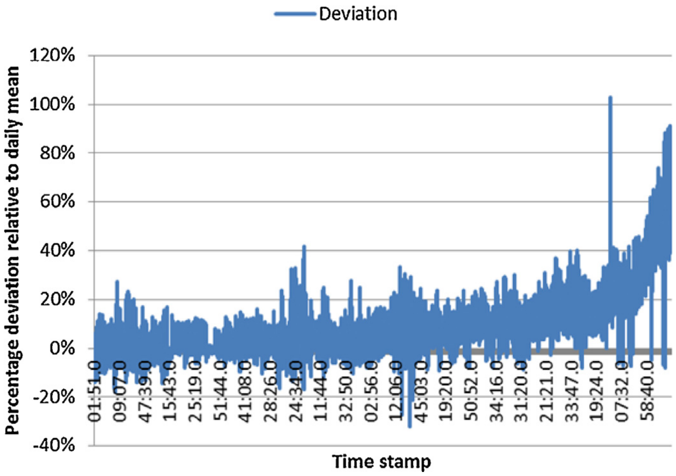

Fig. 9. Deviation parameter for triggering alarms during abnormal vibrations using random forest model.

24 h. For detection, a deviation of greater than 40–50% should be seen as unusual and means that an abnormal behaviour has occurred. Fig. 9 shows the plot of the deviation for a one week time window for the operating period just after of 6 months before failure was observed (using the random forest model as an example). It can be seen that there is a sharp increase in deviation towards the end of the period.

Fig. 10 shows the time series plot of the observed vs. predicted vibrations. It can be seen that even though the observed vibrations were not so high (compared to Fig. 10. Where the time window was extended to include the period failure was detected), there was signs that the observed values were abnormal (deviating from the expected values for a consistently long period and not randomly). Furthermore, Fig. 11 shows that the vibrations had reached extremely high levels and at this point, the failure had propagated into a critical state where debris from cracked bearing inner rings became visible to the naked eyes during visual inspections. Hence, the use of remote monitoring would have ensured that the failure was detected at a much earlier stage hence enabling more proactive maintenance planning and avoiding consequential damage from broken pieces of metal which contaminate the gearbox lubrication system.

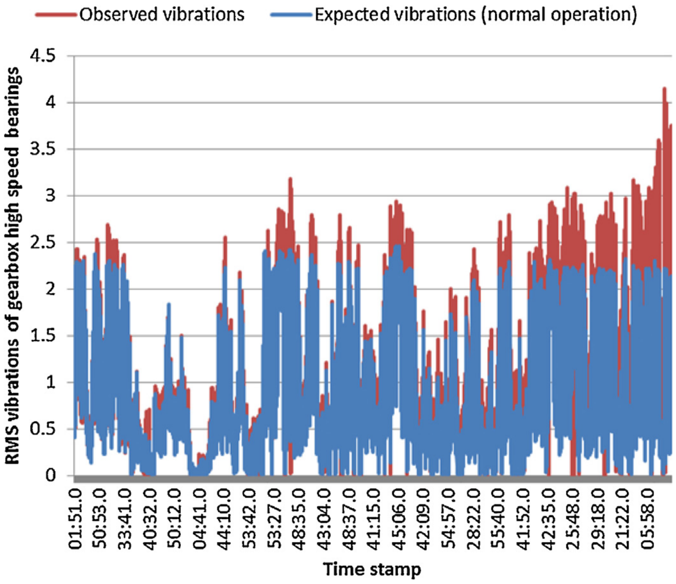

Fig. 10. Observed vs. predicted vibrations for time window just after 6 months before failure was observed.

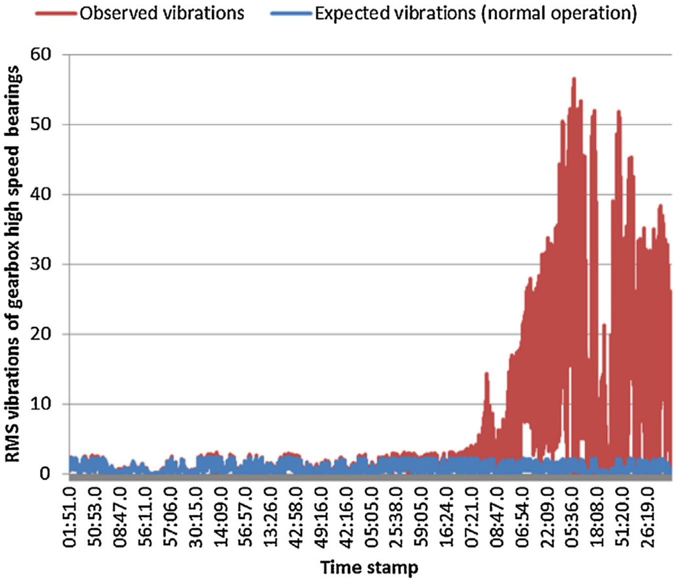

Fig. 11. Observed vs. predicted vibrations for time window between 6 months before and 1 week after failure was observed.

Continuous learning and optimisation

Another aspect, if not the most important, which is necessary for implementing TES technically is process by which in-service knowledge is captured, fed back and reused. Researchers such as Goh and McMahon [10], Doultsinou et al. [45], Meier et al. [7], Igba et al. [46] and McMahon and Ball [47], etc. all agree that in-service knowledge is an important ingredient in PD. Furthermore, for PSS companies to continuously optimise the performance of their products throughout the life cycle, the reuse of in-service knowledge must become a norm [8]. This process is also known as continuous learning and optimisation (of both the product and services) in the PSS domain [8]. The product optimisation is focused on the redesign of components (systems) which have shown poor field performance observed from field failure and maintenance data. Many PSS organisations have formal processes and systems for achieving this, either by updating Design FMEAs with operational failure data to redesign components which affect the risk priority number of the original design (which can sometimes be underestimated). The other forms of optimisation include the optimisation of maintenance process and strategy through the combination of design knowledge and insights from operational data, and (ii) the optimisation of detection models (such as those presented earlier) by cross validating the prediction/detection accuracy with the actual failures and events that have occurred in the field.

Fig. 12 describes the process through which this can be achieved in WT TES. The major stages in the process are the capturing of in-service data, together with operational CMS & SCADA data, analysing and trending these data to provide input (feedback) for design, maintenance and CMS optimisation.

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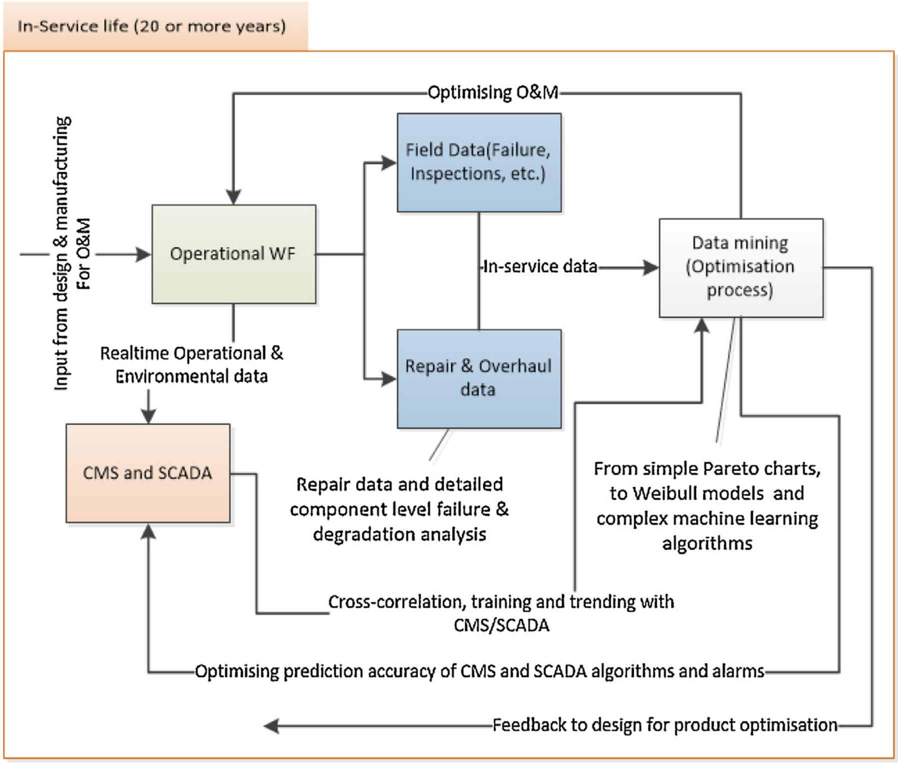

Fig. 12. Continuous optimisation and learning cycle for WT TES [1].

Conclusion and future research

This paper has presented a methodology through which TES can be benchmarked for a manufacturing organisation or relevant industrial sector. This methodology was then use to benchmark TES for WT. The process involved identifying the current practices in WT through-life support defining the requirements TES, and the identifying the challenges and opportunities of TES for WTs. A case study was presented to demonstrate how TES can be benchmarked and implemented for WTs. This focused on gearboxes which are one of the most important components of WTs. Two TES requirements of technical and organisational/operational effectiveness were identified as being the most important for the TES of WT gearboxes. This was the performance of the gearbox is the main selling point of OEMs to their customers and the functionality and availability are crucial to delivering this performance. Furthermore, the organisational/operational aspects are needed to be in place in order to have the right people and processes to deliver the technical performance. A focus on the importance of remote monitoring and the continuous learning and optimisation of product design and O&M processes was discussed. The authors proposed new remote monitoring techniques which help with early detection of faults and proactive planning of O&M in order to ensure that TES requirements are met.

Finally, some of the challenges and opportunities which have been identified in this paper raise new research questions for potential future research in WT TES. From a technical perspective, future research can in particular focus on bridging the gap between the theoretical and actual availability. This will involve more sophisticated modelling approaches which take factors such as weather, transport and site accessibility in to account when calculating the actual availability. Furthermore, there are possibilities to expand the areas of service and technical innovation in WT TES. The former will involve developing new business models which augment TES through the provision of a holistic approach to TES in the wind sector. The later should focus on dealing with the issues faced in O&M. Perhaps more research is needed in pushing the limits of online health monitoring, autonomous maintenance and self-healing technologies so as to address the challenges of O&M.

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References

[1] Igba, J., Alemzadeh, K., Durugbo, C., Henningsen, K., 2014, Through-life Engineering Services: A Wind Turbine Perspective, Procedia CIRP, 22:213–218.
[2] GWEC. 2014, GWEC Global Wind Energy Figures Homepage, . [Online]. Available: www.gwec.net, http://www.gwec.net/global-figures/wind-in-numbers/# [accessed 10.03.14].
[3] Fried, L., 2013, Global Wind Statistics 2013, Report, Global Wind Energy Council (GWEC), Brussels.
[4] Hameed, Z., Vatn, J., Heggset, J., 2011, Challenges in the Reliability and Maintainability Data Collection for Offshore Wind Turbines, Renewable Energy, 36/August (8): 2154–2165.
[5] Alonso-Rasgado, T., Thompson, G., Elfström, B.-O., 2004, The Design of Functional (Total Care) Products, Journal of Engineering Design, 15/December (6): 515–540.
[6] Ward, Y., Graves, A., 2007, Through-life Management: The Provision of Total Customer Solutions in the Aerospace Industry, Journal of Services Technology and Management, .
[7] Meier, H., Roy, R., Seliger, G., 2010, Industrial Product-Service Systems—IPS2, CIRP Annals – Manufacturing Technology, 59/January (2): 607–627.
[8] Igba, J.E., Alemzadeh, K., Gibbons, P.M., Henningsen, K., 2015, A Framework for Optimising Product Performance Through Feedback and Reuse of In-service Experience, Robotics and Computer Integrated Manufacturing, .
[9] Isaksson, O., Larsson, T.C., Rönnbäck, A.Ö., 2009, Development of Product-service Systems: Challenges and Opportunities for the Manufacturing Firm, Journal of Engineering Design, 20/August (4): 329–348.

Please cite this article in press as: Igba, J., et al., Through-life engineering services of wind turbines. CIRP Journal of Manufacturing Science and Technology (2016), http://dx.doi.org/10.1016/j.cirpj.2016.08.003

[10] Goh, Y., McMahon, C., 2009, Improving Reuse of In-service Information Capture and Feedback, Journal of Manufacturing Technology Management, 20/5: 626–639.
[11] Matthews, J., Irvine, N., McInnes, D., 2013, Through-life Engineering for Nuclear Plant, Procedia CIRP, 11/January: 249–253.
[12] Norden, C., Hribernik, K., Ghrairi, Z., Thoben, K.-D., Fuggini, C., 2013, New Approaches to Through-life Asset Management in the Maritime Industry, Procedia CIRP, 11/January: 219–224.
[13] Knowles, M., 2013, Through-life Management of Electric Vehicles, Procedia CIRP, 11/January: 260–265.
[14] Tracht, K., Westerholt, J., Schuh, P., 2013, Spare Parts Planning for Offshore Wind Turbines Subject to Restrictive Maintenance Conditions, Procedia CIRP, 7/January: 563–568.
[15] Tracht, K., Goch, G., Schuh, P., Sorg, M., Westerkamp, J.F., 2013, Failure Probability Prediction Based on Condition Monitoring Data of Wind Energy Systems for Spare Parts Supply, CIRP Annals – Manufacturing Technology, 62/January (1): 127–130.
[16] Aurich, J.C., Mannweiler, C., Schweitzer, E., 2010, How to Design and Offer Services Successfully, CIRP Journal of Manufacturing Science and Technology, 2/January (3): 136–143.
[17] Fähnrich, K., Meiren, T., 2007, Service Engineering: State of the Art and Future Trends, Advances in Services Innovations, 3–16.
[18] Walford, C., 2006, Wind Turbine Reliability: Understanding and Minimizing Wind Turbine Operation and Maintenance Costs, Sandia National Laboratories, New Mexico, Albuquerque.
[19] McNiff, B., Musial, W., Errichello, R., 1990, 1991, Variations in Gear Fatigue Life for Different Wind Turbine Braking Strategies, AWEA Wind Power', 90/September.
[20] Igba, J., Alemzadeh, K., Durugbo, C., Henningsen, K., 2015, Performance Assessment of Wind Turbine Gearboxes Using In-service Data: Current Approaches and Future Trends, Renewable and Sustainable Energy Reviews, 50:144–159.
[21] Dykes, K., Meadows, R., Felker, F., Graf, P., 2011, Applications of Systems Engineering to the Research, Design, and Development of Wind Energy Systems, .
[22] Jin, T., Ding, Y., Guo, H., Nalajala, N., 2012, Managing Wind Turbine Reliability and Maintenance via Performance-based Contract, Power and Energy Society, 1–6.
[23] García Márquez, F.P., Tobias, A.M., Pinar Pérez, J.M., Papaelias, M., 2012, Condition Monitoring of Wind Turbines: Techniques and Methods, Renewable Energy, 46/October: 169–178.
[24] Yang, W., Tavner, P., Crabtree, C., Feng, Y., Qiu, Y., 2012, Wind Turbine Condition Monitoring: Technical and Commercial Challenges, Wind Energy, 17/5: 673–693.
[25] Igba, J., Alemzadeh, K., Henningsen, K., Durugbo, C., 2014, Effect of Preventive Maintenance Intervals on Reliability and Maintenance Costs of Wind Turbine Gearboxes, Wind Energy, ;(September).
[26] Feng, Y., Qiu, Y., Crabtree, C., Long, H., Tavner, P., 2013, Monitoring Wind Turbine Gearboxes, Wind Energy, 16/5: 728–740.
[27] Berkhout, V., Faulstich, S., Görg, P., Kühn, P., Linke, K., Lyding, P., Pfaffel, S., Rafik, K., Rohrig, D.K., Rothkegel, R., Stark, E., 2012, Wind Energy Report Germany 2012, Kassel.
[28] Fischer, K., Besnard, F., Bertling, L., 2012, Reliability-Centered Maintenance for Wind Turbines Based on Statistical Analysis and Practical Experience, IEEE Transactions on Energy Conversion, 27/March (1): 184–195.
[29] Igba, J., Alemzadeh, K., Durugbo, C., Eiriksson, E.T., 2016, Analysing RMS and Peak Values of Vibration Signals for Condition Monitoring of Wind Turbine Gearboxes, Renewable Energy, 91:90–106.
[30] Crabtree, C.J., Tavner, P.J., 2011, Condition Monitoring Algorithm Suitable for Wind Turbine Use, IET Conference on Renewable Power Generation (RPG 2011), 162.
[31] Musial, W., Butterfield, S., McNiff, B., 2007, Improving Wind Turbine Gearbox Reliability, European Wind Energy Conference, .
[32] Feng, Y., Qiu, Y., Crabtree, C., Long, H., Tavner, P., 2011, Use of SCADA and CMS Signals for Failure Detection and Diagnosis of a Wind Turbine Gearbox, EWEA, .
[33] Utne, I.B., 2010, Maintenance Strategies for Deep-sea Offshore Wind Turbines, Journal of Quality in Maintenance Engineering, 16/4: 367–381.
[34] Yang, W., Court, R., Jiang, J., 2013, Wind Turbine Condition Monitoring by the Approach of SCADA Data Analysis, Renewable Energy, 53/May: 365–376.
[35] Wilkinson, M., Darnell, B., 2013, Comparison of Methods for Wind Turbine Condition Monitoring with SCADA Data, EWEA 2013 (February), .
[36] Durstewitz, M., Ensslin, C., Hahn, B., Rohrig, K., 2006, 15 Years Practical Experiences with Wind Power in Germany, .
[37] Spinato, F., Tavner, P.J., van Bussel, G.J.W., Koutoulakos, E., 2009, Reliability of Wind Turbine Subassemblies, IET Renewable Power Generation, 3/4: 387.
[38] Faulstich, S., Hahn, B., Tavner, P.J., 2011, Wind Turbine Downtime and Its Importance for Offshore Deployment, Wind Energy, 14/July 2010: 327–337.
[39] Smolders, K., Long, H., Feng, Y., Tavner, P., 2010, Reliability Analysis and Prediction of Wind Turbine Gearboxes, European Wind Energy Conference (EWEC 2010), no. EWEC, .
[40] Van Bussel, G., Peltola, E., Henderson, A.R., Morgan, C.A., Smith, B., Barthelmie, R., Argyriadis, K., Arena, A., Niklasson, G., 2001, State of the Art and Technology Trends for Offshore Wind Energy: Operation and Maintenance Issues, in: Proceedings of Offshore Wind Energy Special Topic Conference, .
[41] Knezevic, J., 1997, Systems Maintainability, First Ed. Chapman & Hall, London.
[42] Link, H., LaCava, W., Van Dam, J., McNiff, B., 2011, Gearbox Reliability Collaborative Project Report: Findings From Phase 1 and Phase 2 Testing, .
[43] Kaplan, R., Norton, D., Horvőth, P., 1996, The Balanced Scorecard, .
[44] Bond, T., 1999, The Role of Performance Measurement in Continuous Improvement, International Journal of Operations & Production, .
[45] Doultsinou, A., Roy, R., Baxter, D., Gao, J., Mann, A., 2009, Developing a Service Knowledge Reuse Framework for Engineering Design, Journal of Engineering Design, 20/August (4): 389–411.
[46] Igba, J., Alemzadeh, K., Gibbons, P., Friis, J., 2013, Framework for Optimizing Product Performance Through Using Field Experience of In-Service Products to Improve the Design and Manufacture Stages of the Product, Advances in Sustainable and Competitive Manufacturing Systems, 15–27.
[47] McMahon, C., Ball, A., 2013, Information Systems Challenges for through-life Engineering, Procedia CIRP, 11/January: 1–7.

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