Prognostics and Data Modeling that Extend the Remaining Useful Life of Wind Turbines

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Executive Summary

Wind energy continues to grow in popularity as a source of renewable energy. In 2012, 42% of all new energy generating capacity is attributed to wind turbines making it the #1 source of new capacity. Managing the use of wind turbines has been exceptionally challenging because their operating lifetime is only for five to thirteen years which is much lower than the expectation that they will last between 20 and 30 years.

The main source of premature failures is the gearbox but the source of these failures has not yet been determined. As a result, wind farm operators must evaluate the asset risk of their turbines because the average cost of fixing a wind turbine is between $ 300,000 and $ 700,000 per failure. This means wind farm operators can readily incur costs ranging in the millions of dollars to deal with turbine failures.

> "42% of all new energy generating capacity is attributed to wind turbines making it the #1 source of new capacity."

Currently, the wind industry uses a diagnostics-only technology known as CBM to monitor turbines. But, this approach can be problematic because one to two years of data are needed to better understand the source of failures. In addition, the sensors used to collect the data can generate false positives and also not operate properly. Wind farm operators may need to use an extensive amount of monitoring equipment and hire additional personnel to monitor and evaluate the data leading to additional costs with an uncertain ROI.

Sentient Science has developed a prognostics based computational solution called DigitalClone™ that can simulate the real world operating conditions seen in wind turbines. DigitalClone uses a "ground truth" model that represents the specific wind turbine and how it reacts under different operating conditions.

DigitalClone can provide an accurate prediction of the performance of a specific wind turbine down to its microstructure and accurately predict its RUL. This prognostics approach can be used to simulate "what if" scenarios to enable wind farm operators to change operating conditions to optimize performance.

The result is the wind farm operator can focus on predicting failure instead of looking for indications of failure within data. DigitalClone runs itself enabling the wind farm operator to focus personnel on other tasks which leads to greater productivity.

DigitalClone™ can evaluate all mechanical systems in a wind turbine and has the ability to study a specific parameter using a parameterized model. This parameter can be changed to see how this affects operating life and reliability.

Prognostics can predict what the future failure looks like and take steps to help the wind farm operator extend RUL.

Among the parameters examined by DigitalClone to extend RUL are de-rating, surface treatments, lubricant selection, the right type and timing for remanufacturing and parts from specific OEMs.

The benefits of DigitalClone can lead to a substantial ROI for wind farm operators. Initial estimates indicate that savings of $ 150,000 per turbine per gearbox replacement can be achieved in this manner.

DigitalClone will enable wind farm operators to more efficiently manage their facilities through the development of significant cost savings and lower overhead.

Prognostics & Data Modeling that Extend the Remaining Useful Life (RUL) of Wind Turbines

Capturing kinetic energy from the wind and converting it into electricity is becoming more extensively used. The attractive nature of this renewable source of energy is that wind is present in most regions of the world.

The American Wind Energy Association indicates that total installed wind capacity in the US at the end of 2012 was 60,007 MW.1 This organization also states that 6,700 new wind turbines were installed in 2012 representing 13,131 MW of added capacity.

Wind energy has enjoyed significant growth in 2012 which represented 42% of all new energy generating capacity installed. This makes wind the #1 source of new capacity according to the American Wind Energy Association.

Keske Toyofuku, Chief Information Officer for First Wind provides his perspective on wind energy. He says, “Wind is a renewable, carbon-neutral and low environmental impact source of energy used to generate electricity. This electricity can in turn, be used to power the US national Grid and reduce dependency on fossil fuels.”

With these positive benefits, the assumption might be made that generating energy from wind has proven to be successful. The answer is yes but there have been operating difficulties that have made it more challenging for wind energy companies to successfully manage their facilities.

To start, let's look at the basics of wind energy. A basic wind turbine is shown in Figure 1.

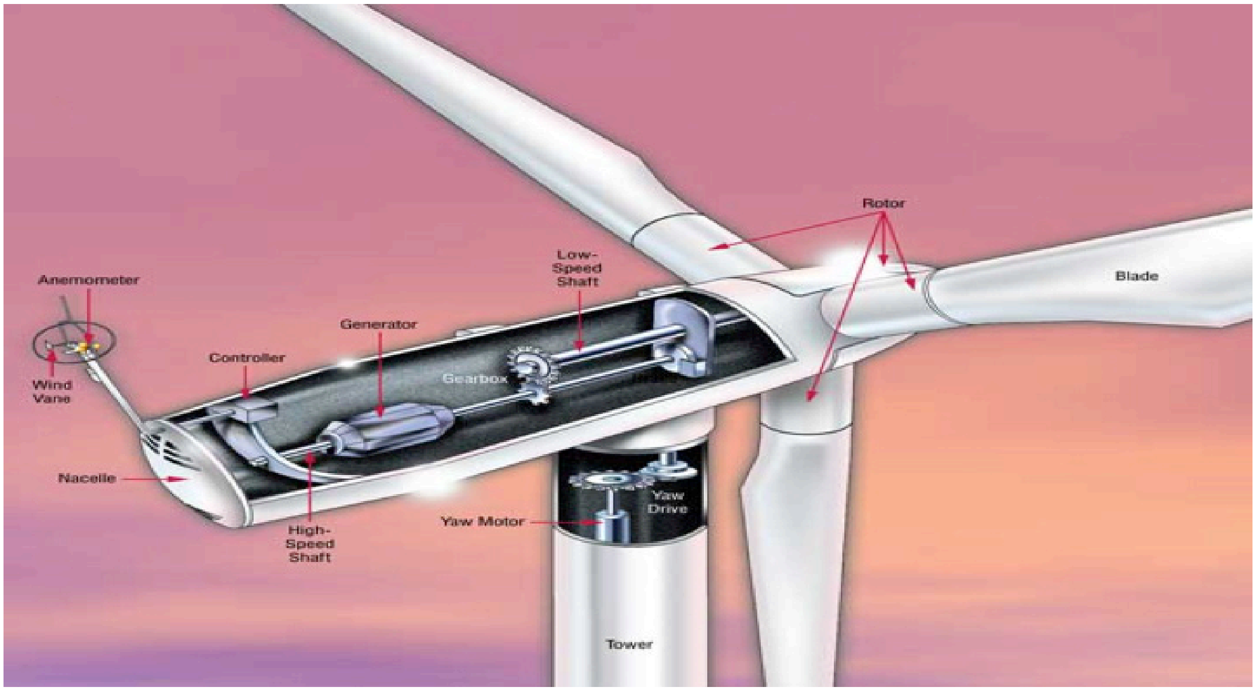

Figure 1: Components in a wind turbine

As the wind turns the rotor blades, the energy captured drives a low-speed shaft. The energy is then transferred through a gearbox that acts in a similar manner to an auto transmission to run a high-speed shaft which then powers a generator used to produce power.

One of the major challenges is the high degree of torque (6 million newton-mm) that can be produced in moving the energy from a low speed shaft (rotating between 10 and 15 rpm) and a high speed shaft (rotating between 1,000 and 1,500 rpm). Compounding the problem is the variability of wind speed conditions that are encountered. This factor can produce added load on the blades, shaft and gears.

Joe Martin, Vice President of Operations for First Wind provides his perspective on working with wind turbines. He says, "Wind turbines are highly automated, dynamic machines that contain hundreds of mechanical moving parts integrated with complex, high-technology electrical power delivery systems. These systems are exposed to the elements in the harshest natural environmental conditions of their regions year round. They are expected to operate faultlessly and mostly unattended, 24/7. Additionally, wind power plants tend to be located in remote or hard to get to locations. Working on wind turbines, in the middle of winter, on top of a mountain in New England or the Pacific Northwest can be challenging at times."

With these difficulties, First Wind was asked about whether the performance of their wind turbines has met their expectations. Martin explains, "Generally, yes, both the parks and wind turbine generators have met our expectation with regards to generation and performance. Due to the number of components and the dynamic environment to which the machines are exposed, expected and unexpected maintenance and repairs are needed from time to time."

The wind industry felt that turbines would last between 20 and 30 years but this goal has not been realized. At this point, turbines have an average lifetime between five and ten years depending upon the manufacturer.

The main source of these premature failures is the gearbox though no industry consensus has emerged about the source of this problem. There is speculation that such issues as fretting wear, micropitting and white etching might account for the failures but none of these mechanisms have been confirmed at this point.

These problems have occurred even though the main lubricant used in wind turbines using the well known synthetic basestock, polyalphaolefin. One option to address the problem of premature failures is to better understand the asset risk and how to take control of that risk.

Stephen Steen, Manager New Business Development Energy and Heavy Machinery Markets for Sentient Science Corporation says, "A key factor that wind farm operators must assess is the asset risk for their turbines. Typically, a wind turbine OEM provides a warranty covering the first two to five years of operation. Beyond that, the operator will have to fix the turbine if it breaks. Currently, the average cost for fixing a wind turbine is between $300,000 and $750,000 per failure." This means that the wind farm operators can face millions of dollars of turbine failures.

One option the wind farm operators have is to purchase an extended warranty from the turbine manufacturer. Steen comments, "OEM extended warranties are available for another ten years of operating life but are very expensive."

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Part of the reason for the high cost of wind turbines is the difficulty in reaching them to do maintenance. In many cases, they are positioned in rural areas (such as mountain tops) and also in off-shore, marine environments.

Martin provides insight on the difficulties that First Wind has encountered in operating wind turbines. He says, "The challenges of operating wind turbines are dynamic and vary greatly. Each specific site presents a host of differing variable. The functional areas of concern when monitoring the machine health center on the blade, gearbox and the electrical delivery systems. Our goal is to develop our current online health monitoring system data into a predictive failure tool."

Currently, the wind industry uses a diagnostics-only technology known as Condition Based Maintenance (CBM) to monitor the condition of turbines. Steen explains, "The wind industry typically purchases a vibration and oil debris sensing system for each turbine type used. For this investment, one to two years of data are needed to get a good understanding of how failures are occurring. The reason for this long period of time is that one to two failures must happen before the wind turbine operator can establish a baseline for how the sensor system will operate."

Having the sensors in place is not guarantee that they will work properly. Steen says, "Sensors can break and have little if any warranty themselves. Regular maintenance activities can also cause sensors to break."

In addition, a significant amount of false positives can take place. Steen says, "Other problems involve the need for an extensive amount of monitoring equipment and the need to hire additional personnel to monitor and evaluate the large amount of data generated by this system. The result is that this technology does a decent job but has significant limitations and costs."

Frank Silvernail, Vice President of Engineering for First Wind comments on what techniques his company has used to troubleshoot wind turbine operations problems. He says, "First Wind has primarily focused on the traditional tools of preventative maintenance, using both time based and reliability centered maintenance. By leveraging our SCADA abilities, we have worked to optimize the different traditional techniques and indicators, such as vibration analysis in a dynamically performing machine, so they can serve as a reliable predictive method."

When asked about the success First Wind has found with using preventative maintenance, Silvernail says, "We have had successes and failures in the application of traditional analytical tools such as vibration analysis. It is a major challenge to implement a reliable method of predicting performance in a dynamic machine."

"It is a major challenge to implement a reliable method of predicting performance in a dynamic machine."

An alternative approach is needed to better predict the failure of a wind turbine and make recommendations for extending operating life. As Silvernail of First Wind indicates, "Troubleshooting wind turbine operations remain our biggest challenge. The ability to successfully and reliably model future machine performance has great tangible and intangible benefits."

Such an approach has now been developed to achieve this goal that is also more flexible and more focused. It has the capability to just look at specific parameters that impact performance and provide a powerful tool to meet as Silvernail indicates, "the biggest challenge for First Wind" and for the wind turbine industry.

Introducing Sentient Science's DigitalClone™

Sentient Science Corporation has developed a prognostics based computational solution called DigitalClone which is a cloud based modeling and simulation software that can accurately simulate the "real world" operating conditions for specific machinery components. Users of DigitalClone can go further to determine how these specific components will function and when they will fail.

DigitalClone operates using a "ground truth" model which is representative of the actual serialized asset and how it reacts under different operating conditions. This approach enables Sentient Science to accurately predict how components will perform down to their microstructure in different applications.

As an example, Steen says, "In vibration analysis, two years worth of operating field data may be required to clearly understand the status of a specific component in a wind turbine and determine when it might fail. Prognostics enables an accurate prediction of the specific component which saves significant time and expense needed to collect and evaluate field data. Further, it enables an accurate prediction of the Remaining Useful Life (RUL) of the serialized asset."

A critical benefit is that DigitalClone can simulate "what if" scenarios to assist users with changing operating conditions so that they can optimize performance. This task can not only help users identify the source of a component failure but also establish parameters that will extend the operating life of a specific machinery component over a long time frame.

DigitalClone functions by correlating the analysis conducted at the macro-level where machinery systems function to the stresses detected at the micro-level in order to predict operating life. Behrooz Jalalahmadi, Manager of the DigitalClone Service for Sentient Science says, "Six computational steps are at the core of our work flow that we use to attack a problem with the goal of obtaining a performance prediction." (A Better Approach for more Efficient Cost Effective Evaluation of Machinery, 2013)

DigitalClone accurately predicts the RUL for a specific component based on the BOM and operating conditions found in that component. Further details on the benefits that can be realized from DigitalClone are found in the “Benefits of DigitalClone for Wind Turbines” section.

Further details on how DigitalClone is used can be found in a recently published White Paper available on the Sentient Science website.2

Sentient Science originally developed DigitalClone in response to a request from the US Government’s DAPRA (Defense Advanced Research Projects Agency) for a new process to more efficiently and effectively evaluate the reliability of equipment while reducing the need to do physical testing.

The highlight of the program was Sentient Science’s validation of 30 years of testing done by NASA on gears. Ward Thomas, President of Sentient Science says, “We pushed a button and did two days worth of computational processing for a much lower figure and validated the large amount of technology NASA had compiled on gears.”

Work has been done by Sentient Science to better predict the remaining useful life of tail rotor gearbox bearings in a UH-60 M Black Hawk Helicopter.3 The main route to failure is caused by spallation damage in tapered roller bearings in the helicopter’s tail. Spall propagation testing is done to assess how this damage progresses. The testing included correlating vibrations to the actual condition of the bearing.

Sentient Science developed a physics-based model using Prognostics Health Management to predict the rate of bearing spallation damage progresses under a specific set of operating conditions. This model accurately predicted both the rate of spall propagation and the damage pattern observed in experiments.

A second example highlights a comparison between empirical test data and modeling data developed by Sentient Science. Bearing fatigue data was obtained from a bearing OEM and DigitalClone was used to develop a model that very accurately predicts the fatigue failure data obtained from a bearing OEM as noted in Figure 2.

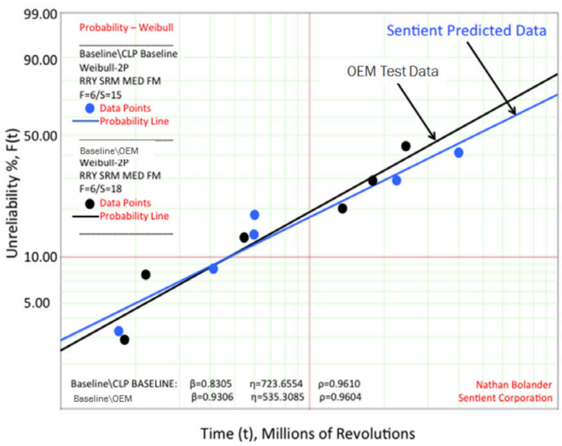


Figure 2: DigitalClone accurately predicted the bearing fatigue data compiled over a long period of time from an OEM.

Use of DigitalClone™ for Wind Turbines

The cloud based modeling and simulation software offered by Sentient Science can readily be applied to boost the reliability of wind turbines. Steen explains, "Prognostics gives us the ability to know future turbine component failure rates and modes and allows us to take actions to minimize them. We follow a five step process when we meet with a customer to achieve this goal that includes the following steps."

1. Connection to SCADA and CBM system for historical and current operations data.
2. Using DigitalClone, build a prognostics model for how the wind turbine or wind turbine farm operates.
3. Make predictions about the state of the wind turbine or wind turbine power plant which includes determining RUL and failure mode, establishing alarms and prepare reports that predict when problems will occur.
4. Establish goals for the ROI of the wind turbine or wind turbine farm.
5. Prepare control settings to optimize the performance of the wind turbine or wind turbine farm.

Prognostics enables the wind farm operator to devote little or no headcount to the vibration or other CBM systems. Steen says, "The service essentially runs itself because it is focused on predicting the failure and what it looks like in the data far ahead of time instead of looking for indications of failure within the data. As a result, the wind farm operator knows what the risks are and more importantly how to reduce them before they happen, preventing the condition from occurring."

The approach is to manage by exception, by only focusing on changes to predictions or sensor data rather than monitoring the data manually looking for indications of failure. All assets in the wind turbine can be managed in this fashion whether the entire system, major subsystems and all the way down to the individual components. The Sentient Science technology is tailored for each specific turbine or wind farm.

DigitalClone is a parameterized model which means that the parameter under study can be changed to see how this affects life and reliability. The result is the wind farm operator can make better informed recommendations on how to improve the operation of the turbines through better design analysis, better understanding of suppliers and determine if components need to be remanufactured to achieve optimization.

Steen says, "The ability of DigitalClone spans all mechanical systems in the wind turbine including the lubricant type, gearbox, pitch system, yaw system, surface finish and geometry. This facilitates the optimum future use of the wind turbine and enables the operator to plan for future use on a per asset basis."

Martin discusses why First Wind was attracted to this prognostics based approach, “The promise of a real time predictive tool using our current individual turbine performance and health systems is substantial. More specifically, the promise of not only the ability to predict gearbox failures, but also the capacity to influence the failure times through proactive operating parameter adjustments has great advantages in reducing operating costs over current utilized platforms. The fact that this technology has already been proven in other markets/technologies also played into our willingness to partner with Sentient for a roll out into the Wind Turbine Sector.”

Figure 3 lists key reasons for using prognostics in improving the operation of wind turbines.

Design for Reliability

- Lubrication type, surface finish, geometry, etc.

Root Cause Analysis

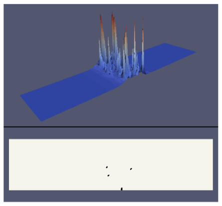
- Identification of root cause, validation of fix

Supplier Validation

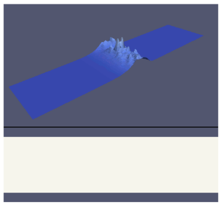
- “Not all Supplier are created equally”

Remanufacturing Optimization

- What parts?
- When to harvest?
- Can I make upgrades?



Ground Finish



Super Finish

Figure 3: Important attributes of Prognostics

The use of DigitalClone is wind turbines offers the operator a great deal of benefits that are detailed below.

Benefits of DigitalClone™ for Wind Turbines

The prognostics approach of DigitalClone provides benefits to wind farm operators from the standpoints of planning preventative maintenance, focusing on only evaluating specific parameters and extending RUL. These three factors are noted in Figure 4.

In progressing from time zero to year 2, the CBM approach often makes it very difficult to figure out the right time to do planned preventative maintenance. Steen says, “With the high cost involved not just from shutting down the turbine but also the logistics involved in reaching the unit, prognostics is a much better approach because it takes the guess work out of the process.”

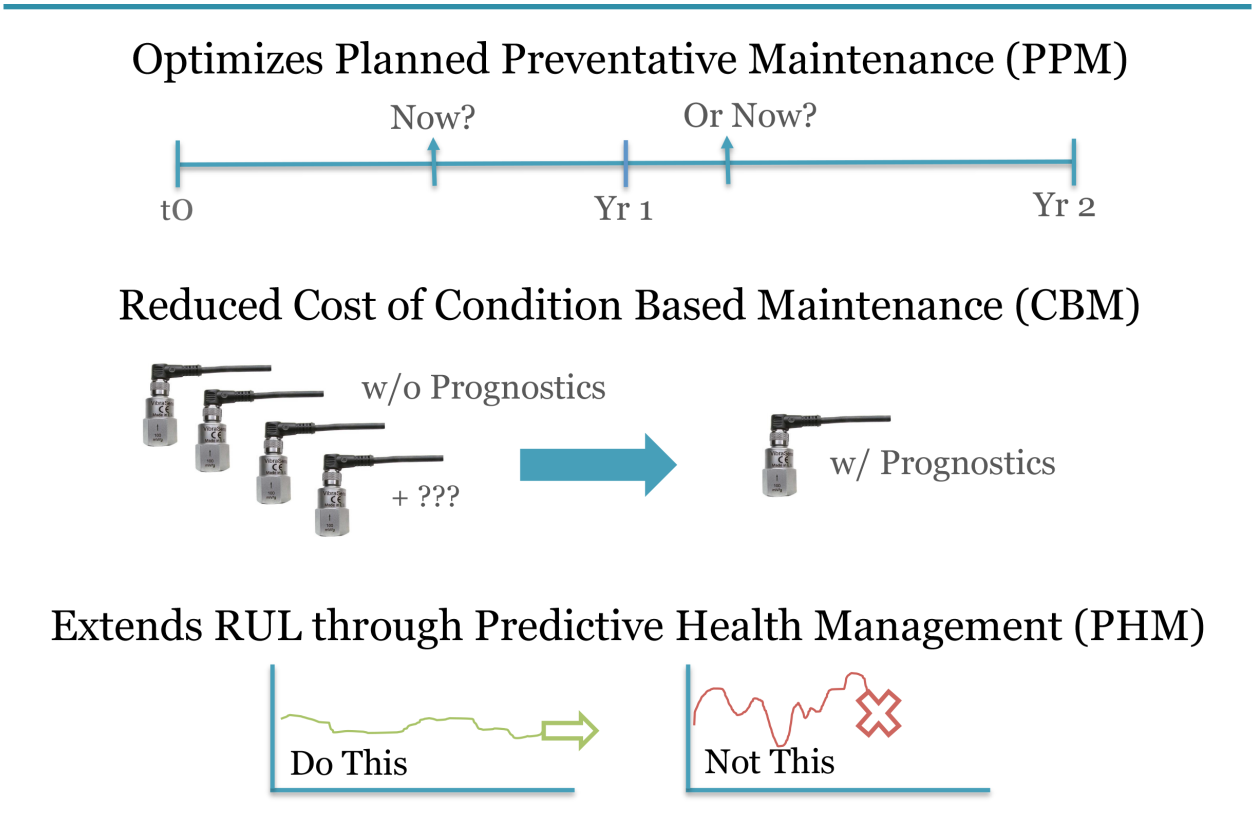


Figure 4: Benefits of Prognostics

Cost is reduced because after the initial evaluation, prognostics is used to determine which of the parameters is most effective in determining potential future failures. Steen says, "In using CBM, there is a tendency to use too many instruments and collect too much data. Prognostics enables the wind farm operator to focus only on a few key sensors that can watch for key failures. The net result is that fewer people are now needed to monitor the wind farm and resources can be reallocated to fix other problems and help the wind farm operator grow its business."

The prognostics strategy using Predictive Health Management can also help to extend RUL through focusing monitoring on specific parameters. This means that the wind farm operator does not have to follow the traditional approach of checking a large number of parameters over short time intervals. Steen says, "Use of prognostics increases the wind farm assets and mitigates future failure rates thereby extending operating life."

DigitalClone is particularly useful as the wind turbine enters the final phase of its operating life. Figure 5 shows a schematic of how the performance of a wind turbine progresses from "Time A" through its functional failure at "Time D".

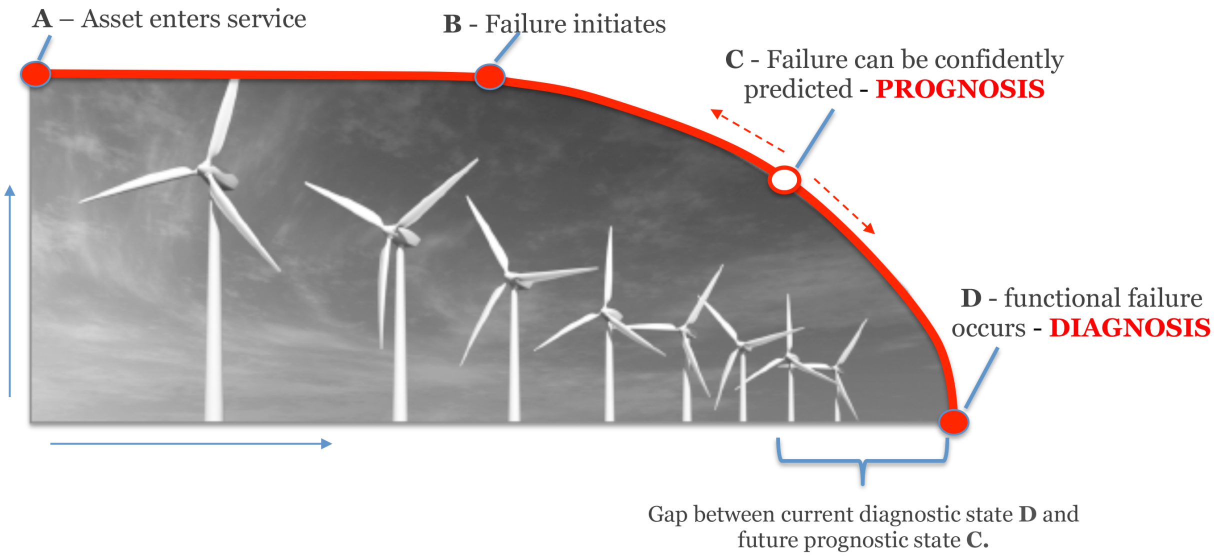


Figure 5: The timeframe for operation of a wind turbine.

Steen says, “Over 90% of its operating life, a wind turbine will develop micro cracks that eventually lead to it spending the remaining 10% of its life in a faulted state and then ultimately functional failure. Prognostics can predict and see what failure looks like in components such as the gearbox. This enables Sentient Science to predict the future state of the wind turbine under its current set of operating conditions and what can be done to extend RUL.”

The objective is to extend the time from when failure can be predicted (“Time C”) to when it eventually occurs (“Time D”). One example for how prognostics can be used is to focus on vibrational signals that originate from the wind turbine’s nacelle as shown in Figure 6.

Steen says, “A rotating system model can be implemented that will show how vibration signals from the components propagate to the housing. This model can simulate these signals, find fault levels and locations and predict premature failure. Our approach has the objective of really fixing the issues that wind farm operators are encountering.” One other benefit of this technology is that the wind farm operator does not need to collect extensive amounts of historical data from monitoring a monitoring system. Once the system is modeled by DigitalClone, a strong analysis can be generated to determine the onset of premature failure and to recommend

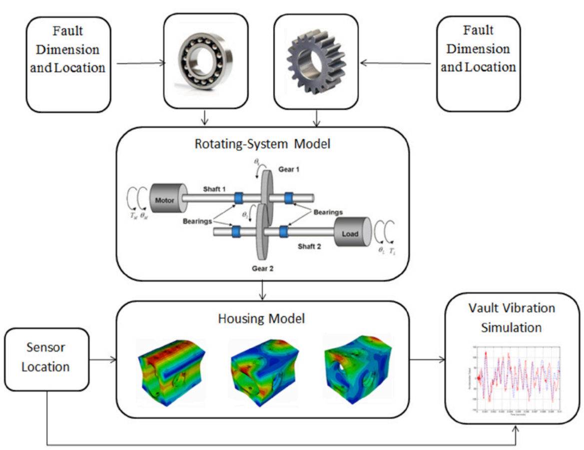
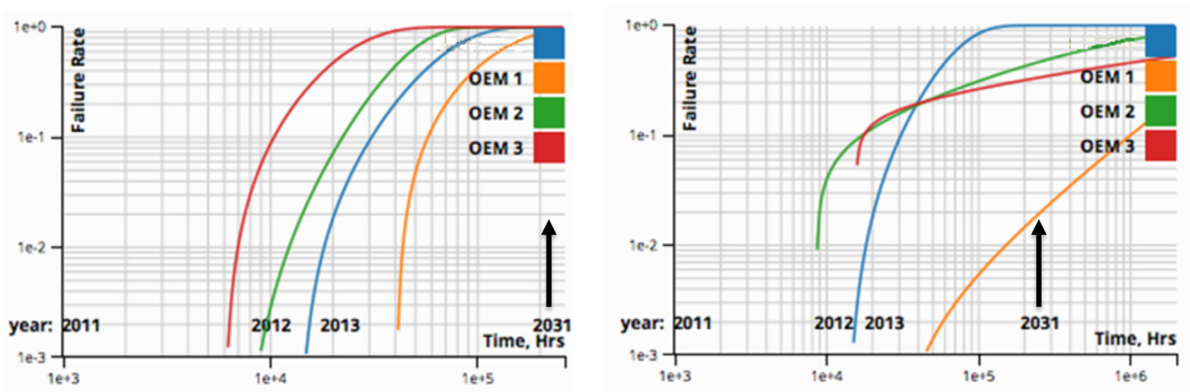


Figure 6: One parameter that can be closely monitored in a wind turbine is vibrational sensor signals through the prognostics approach to more accurately predict failure.

changes in operating parameters to extend and optimize life.

DigitalClone's ability to extend the RUL of a wind turbine is shown in Figure 7. The graph below shows the current failure rate for wind turbines from three OEMs that typically will last between 15 and 20 years. This means that wind turbines produced in the 2012-2013 timeframe will be expected to function until about 2031.

A good prognostics program allows you to quantify "what-if" scenarios to extend RUL.



"As Is" "To Be"

Quantify Impact of:
Lubrication change, auto-lubrication systems, partial de-rating, etc.

Figure 7: RUL can be significantly extended through using prognostics.

Steen says, "DigitalClone can quantify the impact on life of "what if" scenarios that enable the wind farm operator to assess their equipment and figure out the best ways to improve performance in order to lead to improved ROI. Examples include quantifying how changing the lubricant and the lubricant system can improve reliability performance."

One element that can be examined as part of extending the remaining useful life is the concept of de-rating. Steen says, "A specific turbine has a rating to produce a certain amount of electricity (such as 1.5 Megawatts). In de-rating, the turbine's power generation capability can be scaled back so that it produces less electricity (1.3 Megawatts) which serves to reduce loads and torques on the components in the turbine."

This process of de-rating should serve to extend the operating life of the turbine. Prognostics will be able to assist the wind farm operator with determining what set of conditions to use in de-rating to extend the turbine's operations to the maximum extent over its remaining operating life. This includes to what extent the turbine should be de-rated.

Surface treatments to the bearings can also be evaluated by prognostics to determine the best fit for a specific system. Steen says, "Application of a surface finish can lead to improved performance over a longer operating time. Using Digital Clone, we can determine if options such as a Ground Finish or a Super Finish are appropriate for extending the remaining useful life of a specific bearing."

Lubricant selection can also be assessed by Sentient Science's methodology. Most lubricants appear to be virtually identical because they are formulated with a polyalphaolefin basestock. But, specific lubricant manufacturers use different additive packages in combination with the polyalphaolefin basestock. The lubricant picked can have a significant impact on achieving strong gearbox performance over an extended period.

Prognostics can analyze the performance of specific wind turbine lubricants and recommend the best choice for a particular new or used system that will extend its remaining useful life to the maximum possible.

Once a specific component breaks down, DigitalClone can be used to determine the best possible option for remanufacturing the part. Steen says, "There are two options that a wind farm operator can use when a part fails. The first approach is to buy all new replacement parts including internal components. A second way to do this is to replace specific internal components and reuse as many components as possible."

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Prognostics can be used to determine which of these two procedures will work best for a specific wind turbine. In addition, DigitalClone can accurately predict at what stage of failure remanufacturing should be done to get the most operating life out of the existing turbine. As part of the remanufacturing process, Steen points out that recommendations about what type of surface treatment to use can be made during the remanufacturing process.

This flexibility will enable the wind farm operator to maximize the extended remaining useful life of a specific component in the present and in the future.

As part of this process, wind farm operators will be looking at parts from specific OEMs.

For a specific part, DigitalClone will recommend which OEM to select for an application based upon predicting how the parts will perform in a specific wind turbine. This takes the guess work out of trying to decide what OEM to choose.

The use of prognostics in de-rating, surface treatments, alternative lubricants, the right type of remanufacturing and the best OEM parts leads to flattening the operating life curves as shown in the right graph of Figure 6 which means that the wind turbine can conceivably provide optimal performance for time frames in excess of 2031. An added benefit is that DigitalClone's analysis can be tailored to wind turbines manufactured by specific OEMs. RULs for each of these OEMs will move in a different fashion due to difference in how each producer manufactures its wind turbines.

Sarah Lovell, Senior Asset Manager for First Wind speaks optimistically about how DigitalClone will benefit her company. She says, "Gearbox replacement is expensive, requiring a long lead time for replacement parts and scheduling of resources. The promised ability to predict the remaining useful life of our gearboxes will allow us to maximize asset value and optimize the balance of proactive batch gearbox replacement. Also the modeling promises to give early visibility of the gearbox impact of proactive turbine performance optimization initiatives such as wind sector management and fine tuning of blade pitch parameters. The expectation is this tool will open up visibility to maximize the return on the turbine as an asset."

> "The promised ability to predict the remaining useful life of our gearboxes will allow us to maximize asset value and optimize the balance of proactive batch gearbox replacement."

DigitalClone is well suited to dealing with one of the most challenging parameters for a wind farm operator, the weather. If wind conditions can be predicted for the near and long term future, then the prognostics approach is sufficiently flexible to adjust key operating parameters to maximize life. Even adjustments are conceivable to take into account wind variability over specific time frames during a year in a specific location.

The benefits realized from using DigitalClone will lead to a substantial ROI for wind farm operators. ROI assessments with wind farm operators have determined that savings of $150,000 per turbine per gearbox replacement can be achieved through a combination of operating changes such as de-rating, oil filtering, oil replacement and new oil suppliers.

Additional savings can be obtained through optimization of service clustering that allows for optimization of crane use during the low wind season. Steen says, "Hypothetically, assuming a crane mobilization cost of $70,000, we can achieve further savings up to $300,000 a year by grouping turbine failures and pre-ordering gearboxes."

The end result is that wind farm operators achieve significant cost savings and lower overhead through using prognostics to select the optimum equipment and conditions for operating wind turbines. Maximization of wind turbine assets is the main driver as First Wind looks to the future. Lovell says, "First Wind will have the ability to maximize the return on each individual turbine down to the component level. Once proven, this will bring confidence to investors regarding First Wind's ability to predict life cycle and therefore maximize its assets."

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If you have any questions or would like more information about Sentient Science and any of the DigitalClone services, please contact Wesley at wesleythomas@sentientscience.com.