Embracing the Future of the Industrial Internet:

Prognostics and the Next Wave of Data Analytics

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Embracing the Future of the Industrial Internet

Prognostics and the Future of the Industrial Internet

In Daniel Yergin's book, *The Quest – Energy, Security, and the Remaking of the Modern World,* he speaks extensively on energy efficiency, dubbing it "The Fifth Fuel." He explains that the fifth fuel goes by many names: conservation, energy efficiency, energy productivity, and energy ingenuity. However, regardless of the name used, the intent is the same: applying greater intelligence and efficiencies to the way we consume our current energy production will yield as great a—if not greater—benefit as introducing completely new forms of energy production to the market.[1]

Of course, simply suggesting that current energy producing mechanizations ought to run more efficient is easier said than done. It involves a great deal of investment, both in time and dollars. Not only would extensive research and testing be involved under the current environment to test the efficacy of efficiency measures being implemented, but the firm would also have to be assured that their measurements were completely accurate and recorded in real time. Without such assurances, organizational support will likely not follow. Before an organization is willing to invest the time and effort into developing the efficiency of their current production habits in order to realize a greater return on investment (ROI) while also reducing overhead costs, they must first be convinced in the practicality and effectiveness of Daniel Yergin's theory on the fifth fuel.

[1] Daniel Yergin, *The Quest: Energy, Security, and the Remaking of the Modern World* (New York: Penguin, 2012), 620.

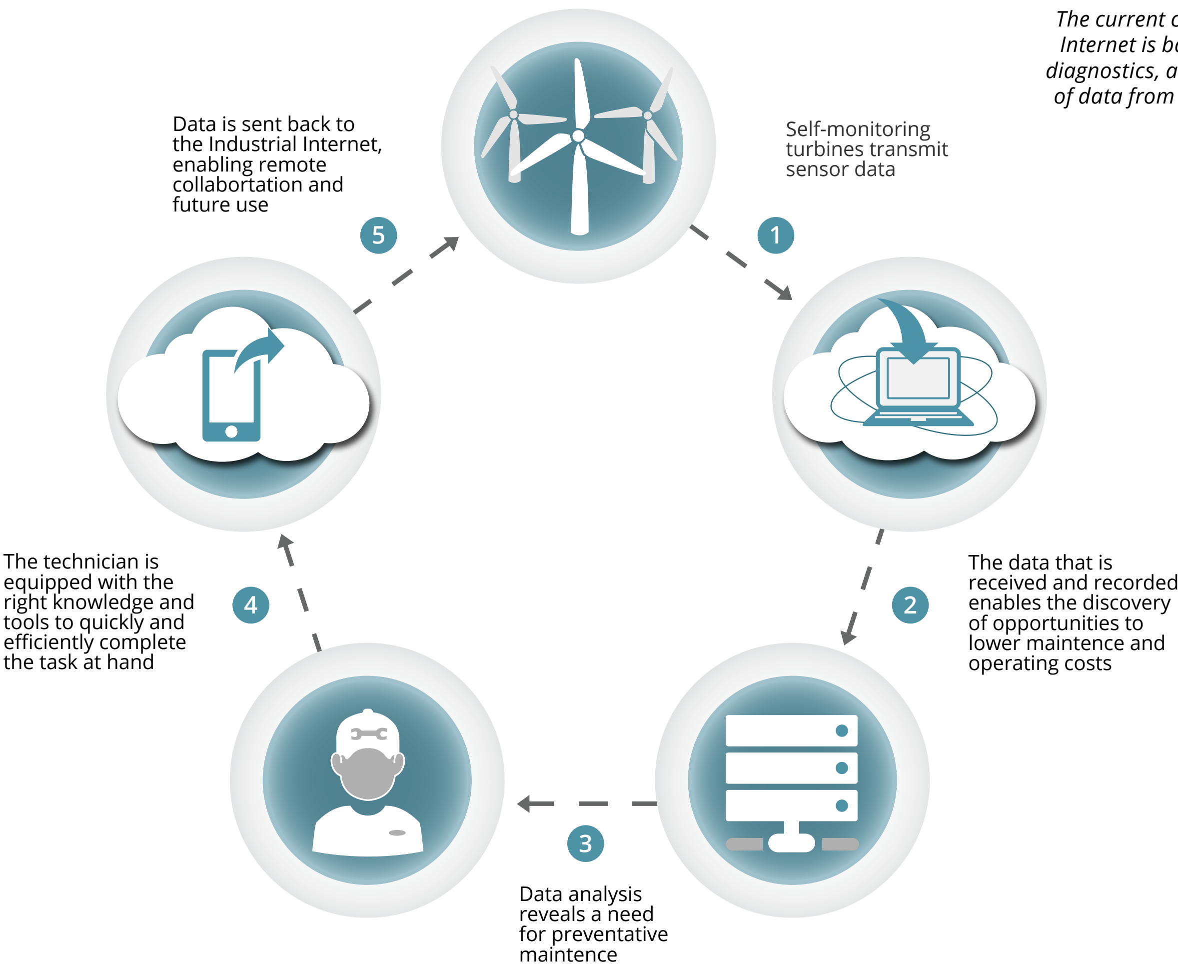
In recent years, the advent of the Industrial Internet has begun answering those concerns through introducing effective monitoring and data collecting capabilities. As General Electric (GE) points out in a recent white paper:

"The Industrial Internet opens the door to a variety of benefits for the industrial economy. Intelligent instrumentation enables individual machine optimization, which leads to better performance, lower costs and higher reliability. An optimized machine is one that is operating at peak performance and enables operating and maintenance costs to be minimized. Intelligent networks enable optimization across interconnected machines."[2]

GE also indicates where the Industrial Internet can have its biggest impact: "One area where the Industrial Internet will make a huge difference is the servicing of the vast quantities of machines, facilities, and fleets that comprise the global industrial system. Millions of different types of equipment need to be operated and maintained, requiring diverse levels of expertise, tools, and time to ensure proper operation."[3]

However, even these initial introductions have their limitations. The current setup within the Industrial Internet relies primarily on diagnostic testing on distributed assets in the field (e.g., a wind turbine operating in a larger wind farm in a remote location) and physical, on-site

The current construct for Industrial Internet is based on the collection, diagnostics, analytics and processing of data from existing fielded assets.



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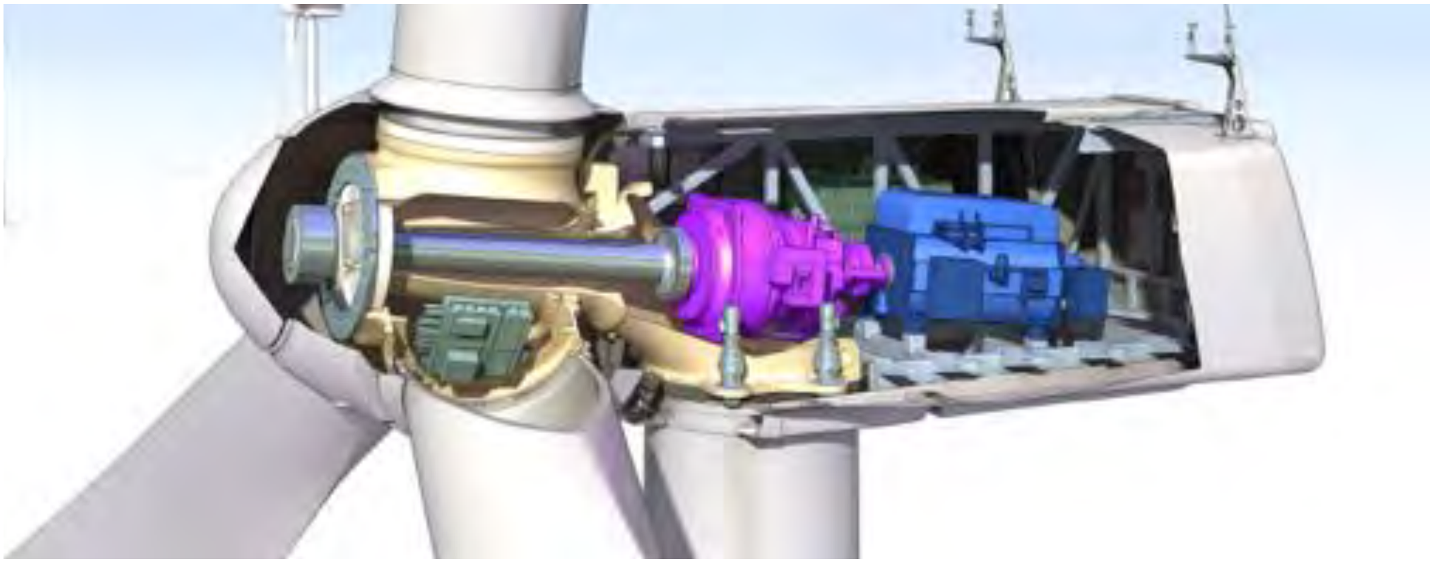
[2] Peter C. Evans and Marco Annunziata, "Industrial Internet: Pushing the Boundaries of Minds and Machines," *General Electric White Paper*, November 26, 2012, 16, (http://www.ge.com/docs/chapters/Industrial_Internet.pdf).

[3] Marco Annunziata and Peter C. Evans, "The Industrial Internet@Work," *General Electric White Paper*, 2013, 14, (https://www.ge.com/sites/default/files/GE_IndustrialInternetatWork_WhitePaper_20131028.pdf).



The customer need is to define critical components and their remaining useful life earlier in the lifecycle of fielded assets providing more time for life extension options. This is especially true in fielded assets with a very high cost of service and replacement.

inspections/repairs. As GE points out, "The time required for the servicing of industrial equipment, and the associated costs, are partly driven by the environment where these activities have to take place. A significant portion of work takes place out in the field, where workers travel to the machine or site. Another portion occurs in service centers, where machines are brought to common shops to be worked on."[4]

One of the greatest pitfalls to diagnostic testing is the increased need for more sensors and ever-greater amounts of data, data storage, analytics, and asset management in order to ensure information accuracy and peak operational output of the machinery. All of these needs put an increasing financial burden on the organization. Yet, there is a solution now establishing itself within the Industrial Internet that will ease the financial burden and increase ROI for in any industry that involves rotating machinery as well. This will be accomplished through the combination of prognostics and system level sensors to confirm initial projections.

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[4] Ibid, 16.

When speaking of prognostics as it relates to the Industrial Internet, we are speaking about predictive modeling based on defined data sets that will reliably predict the future wear and tear a machine is likely to experience through the course of its expected lifetime. Through identifying specific data sets and factors (e.g., weather impact, age of existing machine, source of materials, etc.) prognostic testing will allow the user to predict the output and performance of their machinery. Further, the company will reap the benefits of anticipating true production vs. expected output over the lifetime of the machine. Simply put, prognostics are the next logical step through the Industrial Internet for those seeking a way to reduce overhead and increase efficiencies.

Combining the innovation of the Industrial Internet with the sound, predictable data analytics of prognostic testing will help mitigate machine failure, while increasing operational efficiency and dramatically improving ROI. Prognostics enhance condition-based maintenance (CBM), otherwise known as prognostic health management (PHM). In other words, using prognostic testing will allow the company to gain the greatest return from their machinery while also increasing the overall efficiency during its lifetime. Prognostics combined with the Industrial Internet will be the solution for every industry that is seeking to maximize machinery output, increase their ROI, and better anticipate future outcomes.

1940s
Condition-Based Maintenance (CBM)
Condition-Based Maintenance (CBM) is maintenance performed after one or more indicators show that equipment will fail or performance is deteriorating. **Maintenance when needed arises.**

1970s
Computer-Aided Design (CAD)
Computer-Aided Design (CAD) combines hardware and software that allows engineers to design and render models in three dimensions to be viewed from any angle.

1980s
Computer-Aided Manufacturing (CAM)
Computer-Aided Manufacturing (CAM) is a programming tool that makes it possible to manufacture physical models from CAD.

1990s
Computer-Aided Engineering (CAE)
Computer-Aided Engineering (CAE) simulates performance through a series of mathematical models. Interactive graphic software can then be used to solve engineering problems.

1995
Product Data Management (PDM)
Product Data Management (PDM) is a certified system to manage product data and process-related information.

2000
Product Lifecycle Management (PLM)
Product Lifecycle Management (PLM) is an information and enterprise strategy that allows companies to manage the entire lifecycle of a product.

2013
Prognostics
Prognostics are used by asset managers to extend the remaining useful life of a product.

A history of the modeling technique used for product development and asset management.

Understanding the Current State of Rotating Machinery-Based Industries

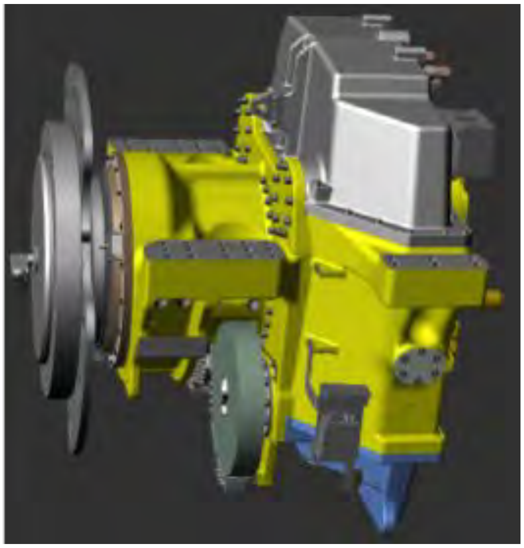
The primary beneficiary of prognostics within the Industrial Internet will be any company with rotating machinery at the core of their operation. In a recent paper, GE estimated that there are over 3 million types of major rotating equipment in use across all industries. This number is an educated guess on their part to best capture the volume of "things that spin" within an industrial system. However, the point remains the same: there is currently millions of spinning components within a multitude of industrial assets spread out across all industries. All of these components are currently subject to monitoring, analysis, and inspection.[5]

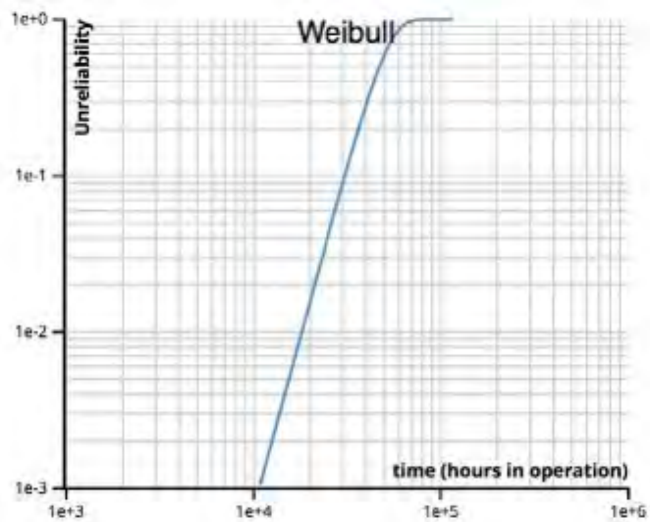
These original equipment manufacturers (OEMs) and operators of equipment companies (asset managers)—ranging from cars and trucks, energy-producing wind turbines and helicopters, to medical implants—will pay over $70 billion over 10 years to protect themselves in the form warranties, protections and reserves. If OEMs and operators gained greater insight into the performance of their machinery and were to take advantage of the efficiencies of prognostics while also aligning their assets under a prognostics-based management (PBM) setup (an idea discussed in greater detail later in the paper), at least 1%-13% of resources could be shifted over to profit rather than protective savings.

For example, according to the American Bearing Association (ABMA), $54 billion in bearings is shipped globally every year, facilitating a rotating market that is estimated at $32 trillion. If the entire industry were to shift to a PBM setup, the industry as a whole would realize what Yergin is referring to when he speaks of the fifth fuel: a dramatic increase in efficiency leading to increased profits and overall savings. In other words, utilizing a PBM setup will help the OEMs and asset managers realize lower costs and increased savings all while still maintaining their current output. In best-case scenarios where the PBM setup is fully taken advantage of, an OEM or asset manager can also experience increased production to go along with the increased savings thanks to the efficiencies gained.

Under current standard operation procedures, diagnostics on specifically tagged assets in the field return data that is collected over expansive lengths of time. This data is then eventually analyzed. In a worst-case scenario, the information returned from the specifically tagged asset might come back and indicate that the asset has already reached operational failure and is no longer functioning at all. Under this circumstance, the OEM or asset manager is losing valuable time where production lacks and costs increase. The OEM or asset manager must determine when the asset experienced operational failure. This will involve a costly effort to send a specialist into the field to physically inspect the asset and bring back the broken portion for further testing and analysis. During this time, they are down one operational asset in the field and without the income it was generating. In all, two months will be spent identifying the cause for the breakdown, determining whether to repair or replace the broken asset, and installing either the repaired asset or replacing it completely. For offshore equipment, the timeframe and cost for repair after a breakdown is significantly higher.

[5] Evans and Annunziata, "Industrial Internet: Pushing the Boundaries of Minds and Machines," 16, (http://www.ge.com/docs/chapters/Industrial_Internet.pdf).





Simulations now exist to calculate the risk of performance failure overtime using multi-physics-based models running over large computing clouds. Weibull's and S-N curves are generated as output reports.

Presently, OEMs and asset managers are experiencing lesser ROI while their maintenance and upkeep costs continue to rise. Discovering a way to extend the useful life of machinery while also increasing output is a paramount concern for OEMs and asset managers. In doing so, they can avoid costly and time-consuming efforts to diagnose a problem and determine whether or not to fix or fully replace the faulty machinery. This is the problem that Frank Silvernail, vice president of engineering at First Wind.

"We have close to a gigawatt-worth of wind turbines spread throughout the country and one of the biggest challenges we have is being able to predict the maintenance needs of the turbines, be able to predict the remaining useful life (RUL) that remains in these machines, because it gets quite expensive to schedule and line up all the equipment that is needed for this. So, being able to manage those downtimes, manage those costs and to be able to do predictive maintenance versus a reactive maintenance, that's really how you manage operating your assets."

Discovering a way to extend the useful life of machinery while also increasing output is a paramount concern for OEMs and asset managers.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Prognostics as the Future

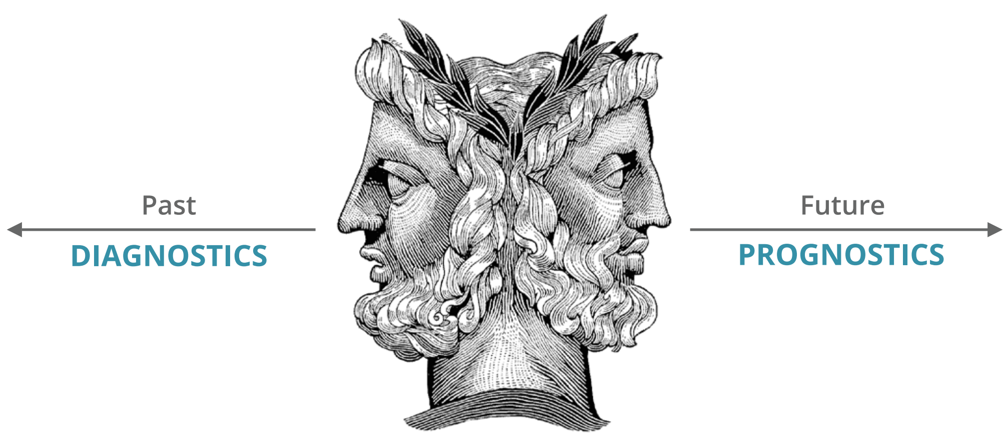
As helpful as diagnostic testing has proven to be in the first wave of the Industrial Internet, prognostics are rapidly showing to be the more effective form of analytical testing moving forward. As GE points out, for the Industrial Internet to develop further, there are certain innovation categories that must be addressed first—which are not currently being met by diagnostics. These include the following areas:

- **Equipment:** Sensors must be integrated and deployed into new industrial equipment as well as retrofitting existing equipment with sensors for the efficient, reliable collection of data and ability to transmit it in real time.
- **Advanced Analytics:** Developing a technical architecture between similar assets will enable the faster data transfers for integration and analysis.
- **System Platforms:** New platforms must be created that will allow firms to build specific applications upon a shared framework/ architecture where multiple groups can share information.
- **Business Processes:** New business practices must be enforced that promote the usage of information gained from machinery analytics to drive business decisions.[6]

Each of these factors considered by GE is addressed in full using prognostics. Whereas the diagnostic setup will only allow for singular factors to be separated and tested in an isolated environment at once, prognostics allows for multi-physics, model-based predictions. That is, prognostics allows for modeling all potential factors an OEM or asset manager envision might affect the output and functionality of it's asset and test them all at once to best ascertain the potential output of the asset in question.

This is the idea of PBM in action. PBM offsets the costs typically associated with CBM. In the CBM setup that is currently used most often many costly variables such as sensors, data warehousing needs, and monitoring must be set up in order to collect data. All of these elements require steep upfront investments that can cost the OEM or asset manager. In the PBM setup described above, the OEM or the asset manager benefits from receiving the predictive models up front, which cuts down on the need to invest in more sensors or greater amounts of data warehouse space.

Multi-physics, model-based testing also has another major benefit over the standard diagnostic testing currently in practice. Through this form of testing, prognostics will help accurately predict machine failure *before* the machine breaks down. Alerts will sound well before breakdown thereby affording the OEM



Diagnostics look backward in time. Prognostics look forward in time.

[6] Ibid, 31.

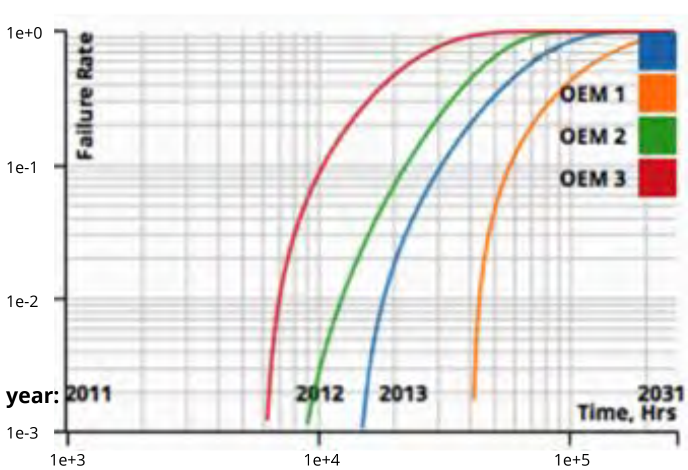
and asset manager ample time to develop a plan of action before the situation becomes catastrophic to operations. It's important to note that understanding the exact usage of a machine is vital in order to manage the system from a remote location. By running multi-physics, model-based testing *prior* to activating the machine, the OEM or asset manager will have valuable insight into the expected performance of the asset before investing heavily into its installation and operation. Through extensive prognostic modeling, the OEM or asset manager can input a wide range of factors into the testing to account for the myriad scenarios that the asset might encounter in the field, such as accounting for the environment where the asset will be placed; the weather conditions it will face; potential human error during installation or maintenance; and general wear and tear over time. This form of testing will help the company save on costs related to repair and potential removal, especially in the case of extreme condition machinery. If you can anticipate the failure, you can circumvent the issue before it occurs and leads to total breakdown.

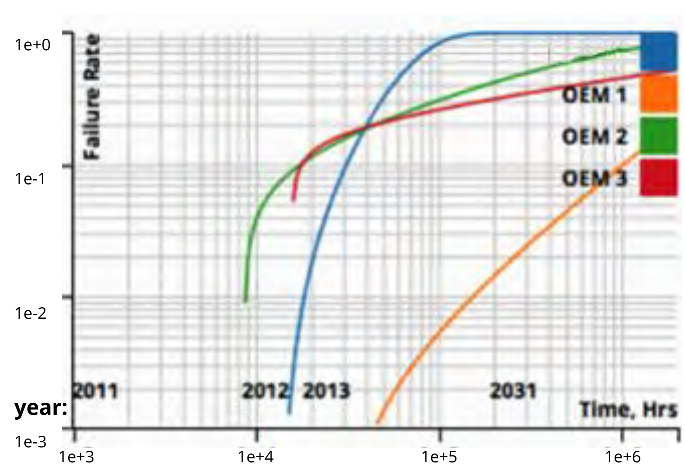
Employing prognostics helps offset extraneous costs, being that 70% of the costs are in the upkeep and maintenance of existing hardware.

If the weakest component within the machinery can be identified at the onset through multi-physics, model-based testing, the OEM or asset manager has the luxury of deciding to remove the weak component and replacing just that part before placing the asset online, rather than being forced to prematurely replace the entire asset before it can reach its expected life expectancy.

Crack Initiation Testing through Prognostics

Prognostics can provide risk assessments for a fleet of assets or even a singular asset. Through failure modeling testing such as a crack initiation test, a fleet of assets or a single asset can be assessed for failure rates. The crack initiation test is an extremely effective method to predict the operating life of an asset. Once any component within the machinery starts to crack in any way, it won't be long thereafter that the entire asset meets operational failure. Through crack initiation testing and using prognostics to run thousands of simulations on the specific asset prior to its use in the field, a unique risk profile can be created of the asset that will help inform the OEM or asset manager of its life expectancy and particular points of weakness.





Using DigitalClone, an owner/operator could look at both the "as-is" state of their fleet to understand the existing financial liability they have as more assets fail overtime (left graphic). They can also simulate various maintenance options from de-rating to oil changes to understand the impact and ROI of life extension decisions (right graphic).

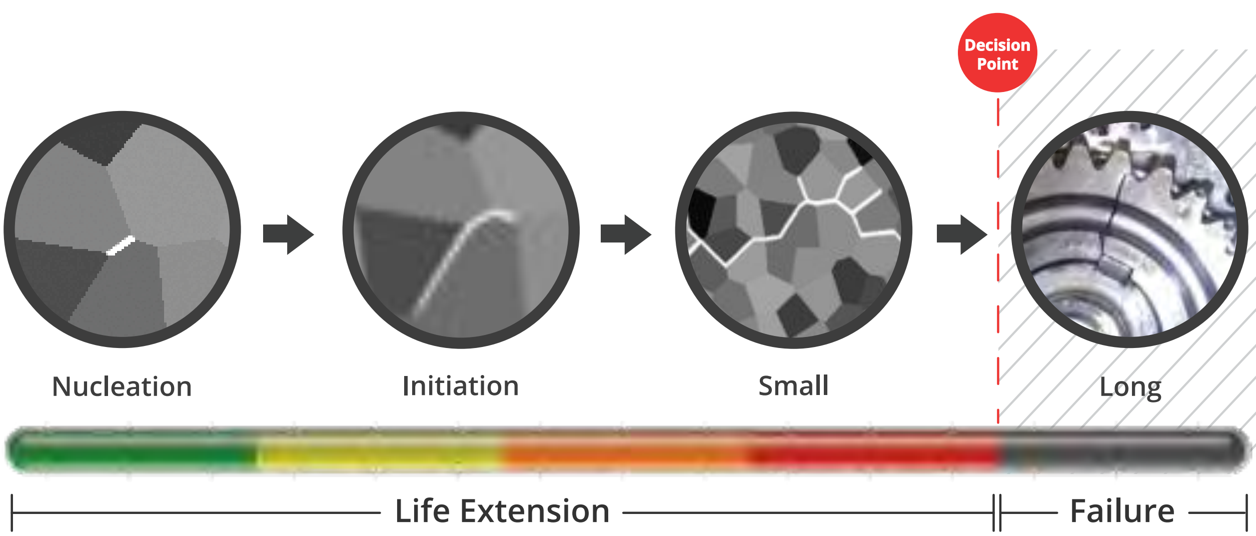
Crack initiation testing is done to identify mechanical failure before it turns into operational failure. Cracks can not been seen or heard through standard observational inspections, but their occurrence begins the degrading process. This is where mechanical failure begins. If unattended, the process can easily accelerate based on extreme operating conditions such as weather conditions, heavy usage of the machinery, and general wear and tear over time. Ultimately, it will lead to operational failure.

Mechanical failure differs from operational failure in that there is still time for the OEM or asset manager to salvage the machinery, whereas operational failure is when the machine can no longer function and produce. Identifying mechanical failure at the onset through early detection measures, such as crack initiation testing through prognostics gives the OEM or asset manager an opportunity to ask two questions:

1. **Can I extend the RUL of the machine at this point?**
2. **Is it practical and economically feasible to fix the part in question in order to extend the RUL of the machine?**

Taking the proactive approach by leveraging crack initiation testing to identify the beginnings of mechanical failure before it reaches operational failure not only extends the RUL of an OEM or asset manager's machinery, but it increases the efficiency and overall output of the fleet without having to suffer the costly alternative of reacting to operational failure.

The only way an asset can currently be tested using diagnostics is through physical, onsite inspection or through review of the asset post-failure. With crack initiation, the OEM and asset manager can run a two-pronged approach to asset management and preventive care. As previously mentioned above, the first method is to look at the "as is" state of the fleet or singular asset prior to its activation. This performance analysis will be run based on the specific needs of the OEM or asset manager. The second approach is to monitor the assets 24/7 on a real-time basis to measure for any crack failures that might be developing. Because prognostics can be run both via simulation and through real-time tracking, the OEM or asset manager can thus be assured prior to activation of an asset's reliability, and also be confident that if an unforeseen circumstance befalls a particular asset in the field, the issue can be quickly identified and a plan of action to



Sentient Science's critical point of the technology differentiation is in uncovering crack nucleation in materials before a customer can see, hear or visualize the "mechanical" failure. The earlier an owner can uncover a failure in a critical component, the more options and time they have to make life extension decisions.

If an OEM or asset manager can accurately predict or anticipate when a component will crack, the faulty piece can be immediately pulled from the machine for repair or complete replacement.

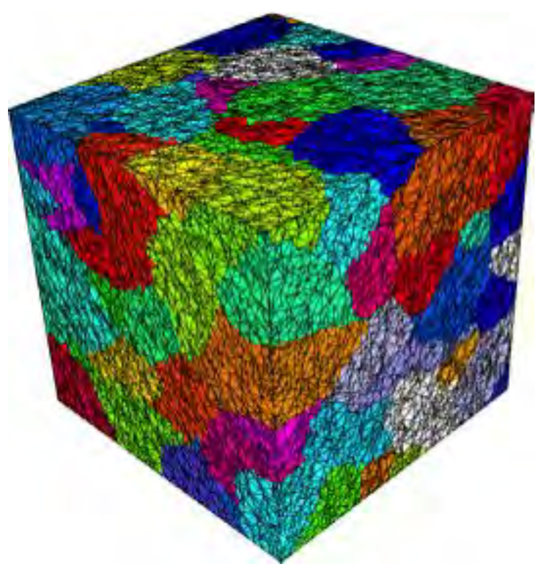
mitigate disaster can be rapidly enacted. Sensors can be placed on rotating equipment to test it and project its life expectancy by identifying any weaknesses within the components.

The logic behind the two-pronged approach is simple, yet effective. If an OEM or asset manager can accurately predict or anticipate when a component will reach mechanical failure, the faulty piece can be immediately pulled from the machine for remanufacturing – meaning, repair or complete replacement. This approach enhances the efficiency of the asset by providing ample opportunity to fix the weak/near-broken part before the entire machine is inoperable. This alternative is a far cheaper and much more efficient than waiting for operational failure to occur and being forced to replace the entire machine.

Taking advantage of prognostic testing—whether prior to deployment or while the asset is in the field—drastically cuts down on testing time currently experienced under diagnostic testing. Prognostics can be used to test assets and their specific components within hours and days versus the months or years needed for accurate diagnostic testing. Further, this not only leads to greater cost savings, but the ability to improve upon current components and create an even better asset for the future.

The Material Genome and a Stronger Asset

Identifying the failures of a component through a crack initiation test and prognostics leads to a greater understanding of the machinery's material genome. Much like the "human genome project", the idea behind the material genome is to essentially understand the components that make up an asset at the molecular level. By understanding the components that create an asset at the molecular level, well-founded predictions and expectations about the performance of the asset can be made.



DigitalClone uses a material model simulated under actual operating conditions to calculate the probability of cracks forming before a borscope could detect a problem with a critical component.

The federal government recently started the Materials Genome Initiative as an effort designed to discover, manufacture, and deploy advanced materials twice as fast, at a fraction of the cost. They define a genome as "...a set of information encoded in the language of DNA that serves as a blueprint for an organism's growth and development." The ultimate goal of the program is to accelerate the understanding and development of advanced materials through computational techniques, more effective use of standards, and enhanced data management.[7] The use of prognostics in the Industrial Internet to manage rotating machinery, such as assets with roller bearings is how OEMs and asset managers can decode the material genome of their assets and best predict its operational efficacy.

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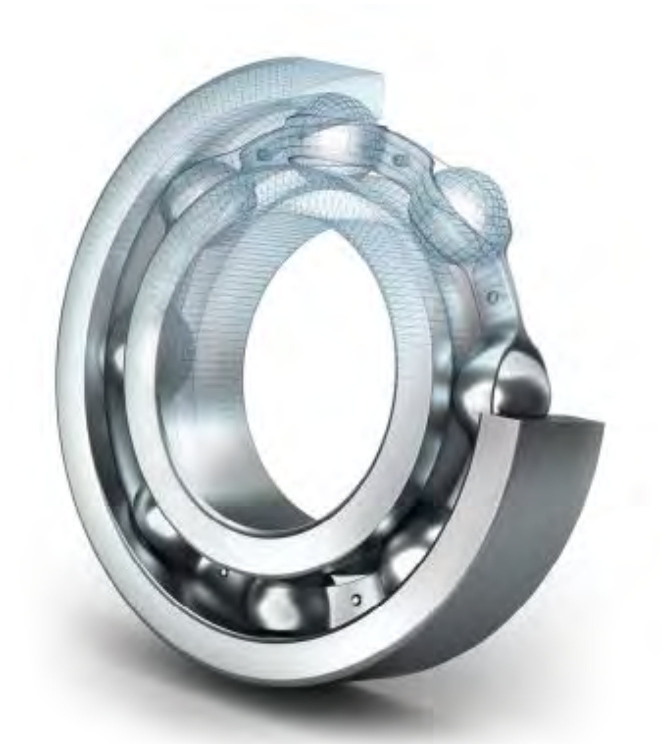
Another way to describe the material genome in relationship to asset management through the Industrial Internet is to consider it in the vein of CBM. By looking at the DNA of the components used to create the asset, the OEM or asset manager can predict what might happen to the asset in the future. Through a greater understanding of the sum of the asset's parts, the OEM or asset manager can be confident that the asset will provide the expected ROI with no disruption.



The power of the DigitalClone prognostic models is its ability to decode the material genome of a specific rotating components, such as a roller bearing, so an operational efficacy can be determined.

[7] National Science and Technology Council (U.S.), *Materials Genome Initiative for Global Competitiveness* ([Washington, D.C.]: Executive Office of the President, National Science and Technology Council, 2011), 4, (http://www.whitehouse.gov/sites/default/files/microsites/ostp/materials_genome_initiative-final.pdf).

Prognostics in Action

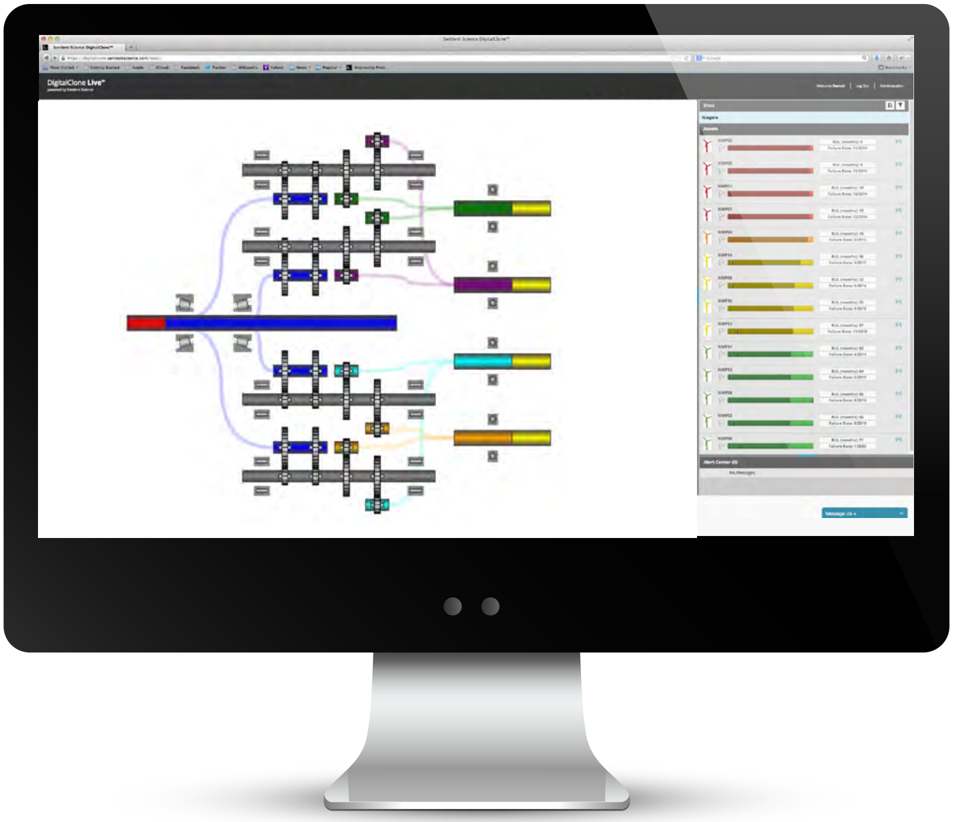
Gaining efficiencies from installed industrial assets provides the highest ROI an OEM or asset manager can experience. Using prognostics has already proven to help OEM and asset managers gain greater efficiencies, and thus, realize substantial cost savings. Through the use of predictive software and prognostics, OEM and asset managers can help keep tabs on their industrial assets and remain a step ahead when determining which assets need servicing and when, thanks to information transmitted by the assets for processing in real time combined with their prognostic analysis ran at the onset. For example, First Wind has reaped substantial benefits by employing prognostics to govern their existing wind farm assets.

Through the use of Sentient Science's prognostics-based computational solution, DigitalClone™, First Wind is beginning to realize an impactful ROI

Using prognostics has already proven to help OEM and asset managers gain greater efficiencies, and thus, realize substantial cost savings.

that has led to strong cost savings and increased efficiency of their existing assets in the field. As First Wind's Senior Asset Manager, Sarah Lovell, explains, "Gearbox replacement is expensive, requiring a long led time for replacement parts and scheduling of resources. The promised ability to predict the RUL 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 find tuning of blade pitch parameters."

DigitalClone is used to calculate the remaining useful life of existing fielded assets and to provide "what-if" options to extend the life of those assets.



DigitalClone integrates a prognostics systems model with diagnostic sensors on a fielded asset to confirm that actual operating conditions either support or require updates of the failure predictions.

Using DigitalClone, FirstWind accurately simulates the “real world” operating conditions for specific components within the windmill’s gearbox. Using a “ground truth” model, which is representative of the actual serialized asset and how it reacts under different operation conditions, FirstWind is able to accurately predict how components will perform down to the microstructure. Further, beyond simply analyzing and testing the core components of an asset, FirstWind is able to subject the asset to extensive hypothetical analysis. Under this “what if” scenario of tests, FirstWind creates a series of potential scenarios their assets might face out in the field to better prepare for unforeseen circumstances and best prepare the assets for these situations, therefore optimizing the performance of the assets.

Using the following six-step process, First Wind was able to analyze the gearboxes of their wind turbines at the macro-level where machinery systems function and correlate it to stresses at the micro-level in order to predict the operating life.

1. Macro-Level Stress Analysis, Load Prediction, and Preliminary Design and Test – This primary step starts with a high level evaluation of the global loads and stresses in a system in order to determine the weak links in design and identify problem issues. Under a traditional diagnostics model, the OEM or asset manager would stop after this step and begin a statistical analysis. However, this first step is akin to a ballpark estimate of the potential stresses endured by an asset and does not provide sufficient backing data to predict the performance of the asset. Therefore, additional steps are required.

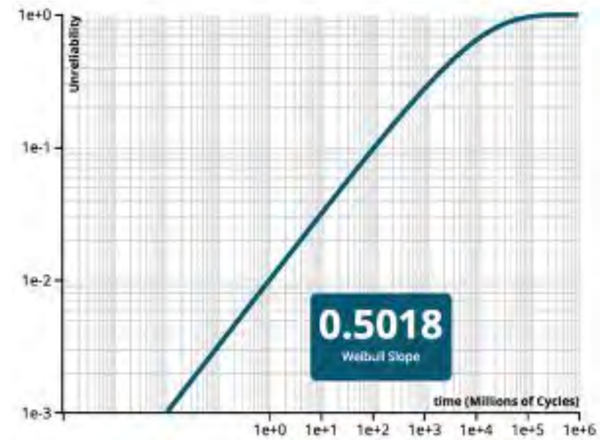
2. Material Characterization and Microstructure Analysis – An in-depth evaluation of the microstructure of the material is conducted from modeling and empirical standpoints. In effect, this is the step that deals with the analysis of an asset’s material genome.

3. Traction Analysis – Traction analysis is conducted to better understand the surface stresses at the micro level. While the surface of a component may appear to be smooth at the macro level after step one, a different picture can emerge when using a microscope to study it at the micro level. This step gives great insight into what happens after two surfaces make contact with another and create friction, but it only serves as the initial insight. An additional step must be carried out to understand how the materials react to the stress caused by the interaction and friction.

4. Microstructure-Based Fatigue Model – Taking the information gained from step 3, step 4 involves applying repeated stresses in the contact zone of two materials to generate data on the reaction of the materials after repetitive contact. During this step, stresses such as the formation of cracks, are simulated and accounted for by the modeling to predict their effect on potential failure. Once a simulation has been run and an understanding of what causes the material to fatigue is established, a model to predict failure can be developed.

5. Run Microstructure-Based Fatigue Model to Failure – The goal of this step is to determine the mechanisms that trigger asset failure and will render the operability of a particular material ineffective. Modeling in this step shows how different mechanisms might be the cause of failure, depending on the various types of stresses that the material might encounter. Once the variables are understood that can cause machine failure, they are tested again to determine what courses of action can be taken to address the issue.

6. Account for Variability in the System Parameters that may have an impact on material life are varied to determine what effect these changes may have to improve or reduce operating life. These simulations can be run repeatedly while changing the variable in order to gain a full understanding of the material's ability to perform under various stresses.



DigitalClone provides critical component-based life predictions that role up to system-wide predictions that roll-up to site and fleet-wide predictions.

Ultimately, the use of a prognostics-based program like DigitalClone and the six-step process described above has provided First Wind significant cost savings and lower overhead. Through prognostics, First Wind can select the optimum equipment and conditions for operating wind turbines. As Lovell says, "First Wind will have the ability to maximize the return on each individual turbine down to the component level."

The windmill industry is not the only industry based on rotating machinery to begin realizing the benefits of prognostics through the Industrial Internet. The aviation industry has also discovered the benefits that come with being able to predict the RUL of the components that make up their machinery. Specifically, companies such as Sikorsky Aircraft Corporation (Sikorsky) and Boeing—who both construct helicopters—have found prognostics and a program such as DigitialClone vital in extending the life of the gearbox in the drive systems.

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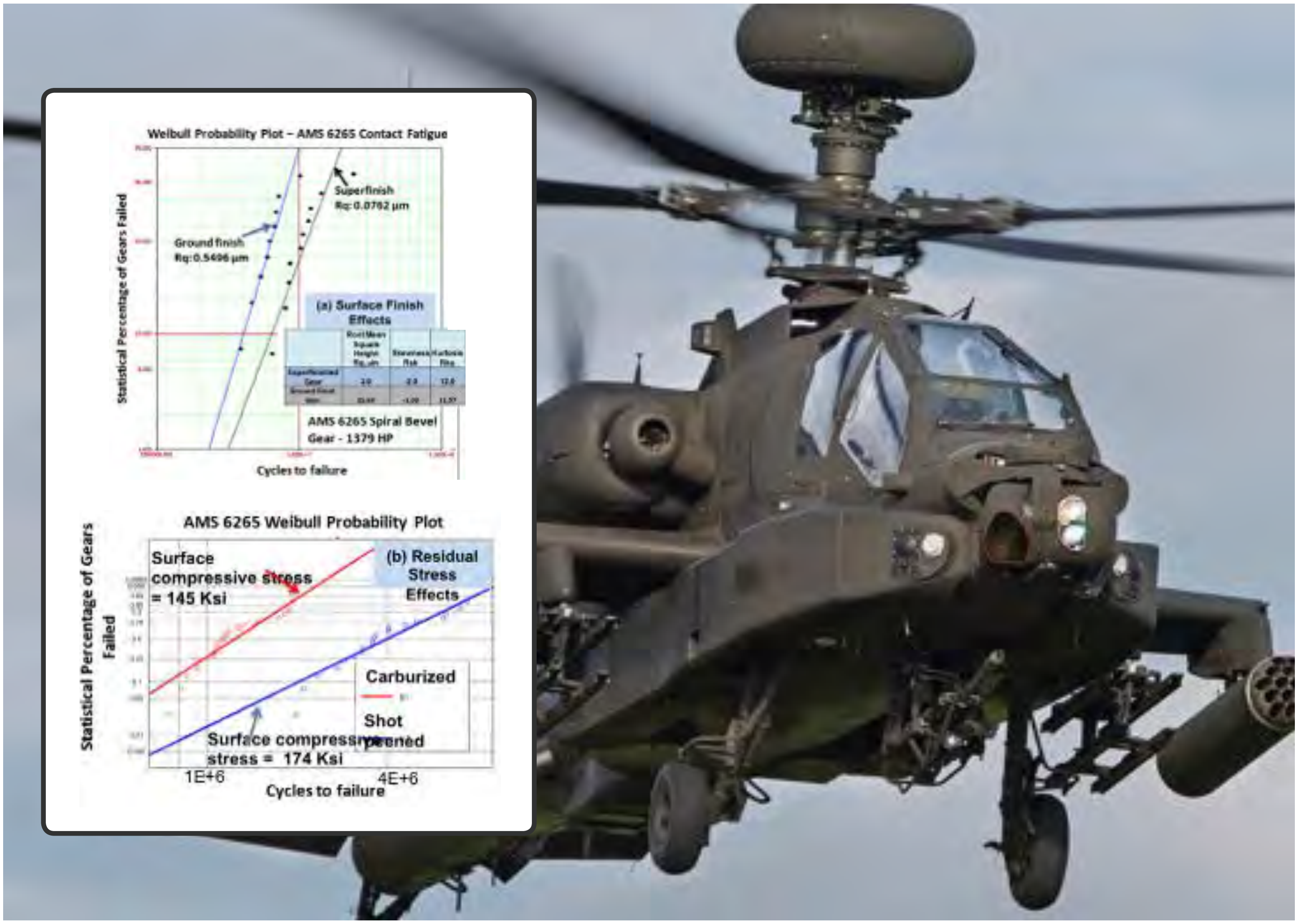

The next generation aircraft will make use of prognostic models to inform the pilot of the remaining useful life of critical components as they change duty cycles during an operational mission.

A key challenge that both Sikorsky and Boeing faced on their respective projects involved the loads associated with the tail rotor drive train. Primarily due to absorbing the brunt of stress caused by maneuvers, the tail rotor drive train generally experiences a more variable range of force than that experienced by the main rotor drive train. Over the life of any particular military rotorcraft, it is not uncommon for the aircraft's operating gross weight to steadily increase, causing the aircraft to fly at higher mean power levels and thus increasing the operating load spectrum associated with the tail rotor drive train. Special missions and unique equipment loads, such as pulling a mine sweeping sled or very high altitude high gross weight assaults, can put severe load demands on the tail drive train.

During these overload conditions the primary failure mode of concern is sudden unpredicted gear tooth fracture. At loads significantly above the endurance limit, tooth fractures can initiate from very small defects and rapidly propagate with potentially catastrophic results. Using PHM via a physics-based model, both Sikorsky and Boeing—in partnership with the U.S Army Aviation Applied Technology Directorate—were able to predict the drive system gears' safe fatigue life when subjected to loads significantly above their rated endurance limit power, or their generally accepted level of tolerance to stress. This means that through the use of PHM, both companies were able to accurately predict the failing point for tail rotor drive trains. This model predicted both the rate of damage propagation and the damage pattern observed in experiments.

Using prognostic models, a design team can examine the overload testing and performance limits of a drive system before beginning physical testing.

Other areas where prognostics and PBM has paid dividends are for those operating heavy vehicles as part of their operations, such as in the construction or mining industry. For example, Industrias Peñoles S.A.B. de C.V. (Peñoles)—the second largest Mexican mining company and the world leader in silver production—utilizes DigitalClone to increase the efficiency of their heavy machinery, specifically, ball mills. Using DigitalClone and PBM to predict and anticipate mechanical failure has allowed Peñoles to lower their costs while increasing overall output.

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Social network

Embracing the Future of the Industrial Internet

Daniel Yergin points out in *The Quest – Energy, Security, and the Remaking of the Modern World* that although industry in general has become more efficient, there is still plenty of savings to be realized. He reminds the reader that technology is an ever-evolving force and is constantly creating new opportunities. He suggests that technological advances such as advanced sensors and computer controls are opening the doors for new innovation that will lead to greater energy efficiency.[8] The development of prognostics within the Industrial Internet is an example of the innovation Yergin is speaking about.

As GE further points out, "A central theme of the Industrial Internet strategy is optimizing asset, operational and business performance."[9] As described throughout this paper, gaining efficiencies from already existing assets in the field provides the highest ROI an OEM or asset manager can realize today, while also dramatically extending the RUL of their operational machinery. To achieve this, prognostics offer the greatest insight available into the material genome of the components that operate an asset. Understanding the composition of an asset through prognostics and the Industrial Internet—be it a windmill gearbox, the gearbox within a tail propeller of a helicopter, or any other rotating component—grants the OEM or asset manager the ability to optimize the output and performance of the asset in question.

Prognostics through PBM will further eliminate the overhead that comes with the standard CBM approach to asset management, thus generating massive cost savings. By using PBM to validate the efficacy of an asset prior to its activation in the field, coupled with measuring the performance of the asset on a real-time basis, OEMs and asset managers remain a step ahead of machine failure. This approach allows OEMs and asset managers to

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[8] Yergin, *The Quest: Energy, Security, and the Remaking of the Modern World*, 625.
[9] Annunziata and Evans, "The Industrial Internet@Work," 18, (https://www.ge.com/sites/default/files/GE_IndustrialInternetatWork_WhitePaper_20131028.pdf).

become proactive, rather than remain stuck in a reactive state, as is the current standard operating procedure.

According to Ed Wagner, vice president at Sentient, "when you look at business plan today, every footnote explains that you can not make forward looking statements. But what if you could? What if you knew the future outcome of that business plan before you invested? Prognostics for in the field, coupled with measuring the performance of the asset on a real-time basis, OEMs and asset managers remain a step ahead of machine failure. This approach allows OEMs and asset managers to become proactive, rather than remain stuck in a reactive state, as is the current standard operating procedure. Machinery can offer that forward-looking view today. You wouldn't manage a business without predictive modeling tools in finance, supply chain operations and sales. Today that level of insight and prediction is now available for your complex machinery."

As Yergin explains in his book, efficiency will be the driving economic engine of the future. "As the world turns over its capital stock—of buildings, vehicles, equipment, and factories—efficiency will be enhanced, because they will embody higher standards of efficiency. As conservation is increasingly seen as a competitive energy source, it will be compared with other investments. In many cases, the economic case for conservation will be very compelling."[10]

For industries with rotating machinery playing a vital role in operations, the case for conservation and the means to achieve it is upon us. Prognostics and the Industrial Internet present the opportunity for vast efficiencies that can lead directly to substantial cost savings in the form of assets that last longer and offer predictable performance at an optimal level.

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[10] Yergin, *The Quest: Energy, Security, and the Remaking of the Modern World*, 630-631.

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