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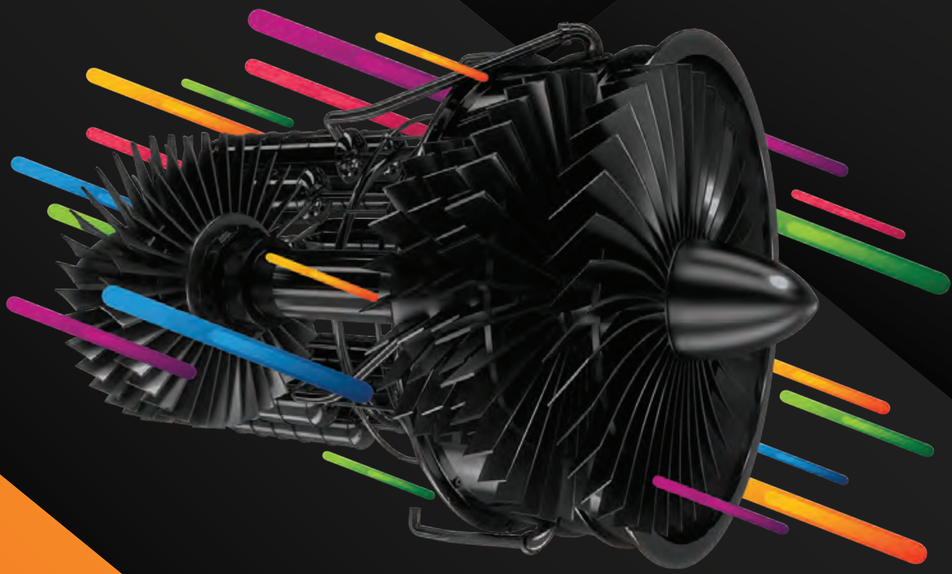


WHITE PAPER

PREDICTIVE MAINTENANCE OF ROTATING EQUIPMENT.

THE WAY FORWARD

A Munich Re company

CONTENTS.

1. EXECUTIVE SUMMARY

Used across industries, rotating equipment is mission-critical in manufacturing. From compressors to pumps to motors, plant profitability revolves around equipment productivity. Reliability is essential. To ensure reliability, operators of rotating equipment seek to keep factors like alignment and balance at peak potential. While this legacy equipment is built to withstand considerable forces of pressure, constant stress on machinery components poses a constant threat of failure and downtime. Rotating equipment users employ condition monitoring strategies to observe the health of machinery components and keep unexpected breakdowns to a minimum by making repairs or replacements before failure occurs.

The next generation of condition monitoring goes beyond 'preventing' failures to 'predicting' failures. Predictive maintenance strategies take advantage of modern sensor technology combined with artificial intelligence technology to offer the user unprecedented levels of insight and predictive analysis.

A holistic predictive maintenance implementation with root cause identification gives the operator a complete picture of the entire system - allowing a deeper level of prediction and analysis that can save on exponential levels of potential financial losses. This shift in thinking from capital and investment to operation and service (CAPEX to OPEX) defines the modern era of manufacturing technology.

The realization that service and maintenance in the life of rotating equipment contain far more value than initial capital investment has prompted the emergence of the subscription or Equipment-as-a-Service (EaaS) model. By externalizing the risks and costs around equipment service to specialists, EaaS promises to revolutionize the industrial landscape at large and empower the users of rotating equipment.

2. MAINTENANCE AND SERVICE CHALLENGES OF ROTATING EQUIPMENT

Considering the scope of pressure points and torsional stress points involved at every connection of rotating equipment, it comes as little surprise that proper maintenance is a priority to keeping runtimes steady and uninterrupted. With high pressure and intense rotational power at the core of these technologies, stress points are focused on the seals, belts, brakes and bearings that connect the moving parts of a rotating machinery asset. **Reliability** is the ultimate goal of keeping rotating machinery at peak production, but ensuring reliability is a constant challenge for a multitude of reasons.

Firstly, maintaining **alignment** is crucial for collinear shafts to ensure minimal stress on bearings, couplings, shafts and other machine components. Angular misalignment of just 0.08 of a degree (or more) has been shown to cut the life of a bearing in half. Technologies such as laser alignment are employed to keep misalignment as low as possible. Keeping the cyclical forces on bearings, shafts and equipment structure under control requires maintaining a **balance** standard such as ISO 21940-11 (rotor balancing). If a rotor is out-of-balance (or falling out of balance), it will impose high levels of strain on bearings and severely diminish their lifespan. Unbalance can be measured (and corrected) by looking at **vibration** data from sensors attached at the bearing locations.

By comparing "natural" frequencies with "unbalance" frequencies, data from these sensors can be continually monitored (condition monitoring) to signal any changes in balance that would otherwise be amplified by resonance and potentially lead to further stress problems. To keep resistance at a minimal level, bearings and gears in rotating equipment require appropriate and continual **lubrication**.

Studies show that mistakes in cleaning, tightening and lubrication are the root cause for some 70% of mechanical failures in rotating machinery.

Dirt, oil and debris in oil sumps and bearings are frequently the cause of premature failure. Bearing life can be maximized by proper lubrication and assuring that lubricants are free of contaminants and of the correct viscosity.

Improper lubrication is frequently identified as a root cause for mechanical failure in rotating equipment. Distressed connections can also be identified via correct implementation of **temperature** and **shock** sensors. Temperature, vibration and shock measurements from IIoT sensors delivered to cloud interfaces can be analyzed and identified by machine operators using AI analysis. The more sophisticated the system, the earlier that potential problem areas can be isolated and corrected before more costly damage occurs.

3. CONDITION MONITORING IN ROTATING MACHINERY MAINTENANCE

Early warning systems are essential in rotating equipment to escape cascading damage chains that lead to exponential damage, repair costs, and, ultimately, failure. Maximizing efficiencies while minimizing downtimes is the name of the game. Condition monitoring and its skillful application make the difference between maximum productivity and extensive downtime. Identifying mechanical faults is a constant challenge for operators of rotating machinery such as engines, motors, turbines, pumps, conveyors, compressors, gearboxes and the like. Most faults are detectable, experts say, though the appropriate sensor technology and IIoT interface is not always installed.

Root causes of failure can be identified with sufficiently advanced condition monitoring whether they be factors of misalignment, unbalance, under lubrication, looseness, etc. Having the right condition monitoring system in place with the right digital solution (AI) gives operators the tools they need to identify root causes of mechanical failure and boost reliability to its highest possible level. Early warning with condition monitoring and eliminating root causes can ensure users of rotational equipment the longest possible life and value on their initial investment (ROI).

CONDITION MONITORING EXAMPLE.

Condition monitoring facilitates a remote review of the assets' health status. It also enables a clear view of the sensor readings associated with the health status.

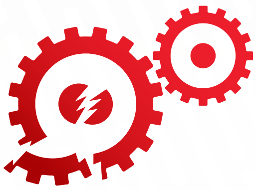
HIGHLIGHTED HEALTH STATES
Highlighting current health status with the most important information

ASSET HEALTH STATUS OVER TIME
Showing asset health state over time and related health events

GENERAL ASSET INFORMATION
Showing the asset name plate data and general asset information to provide context

4. THE THREE MODES OF MAINTENANCE

The necessity of maintenance is unassailable in keeping equipment running as long and as uninterrupted as possible. Within the industrial equipment sphere, there are three major strategies or philosophies about maintaining equipment assets. These three approaches to maintenance can be categorized into these modes: reactive, preventative, and predictive.



1. REACTIVE MAINTENANCE

Fix it when it breaks

2. PREVENTIVE MAINTENANCE

Maintain it regularly, so it doesn’t break down

3. PREDICTIVE MAINTENANCE

Predict when it will break and fix it accordingly

REACTIVE MAINTENANCE is the 'strategy of reaction' or deciding to repair or replace a part only after it has broken or become worn down to the point of failure. Reactive maintenance is perhaps the most basic mode of maintenance in that it can technically require the least amount of work with the highest amount of utilization, all other things being equal. Maintaining by reacting to problems as they arise can create new externalities that become more costly in the end. Unexpected breakdowns created by parts breaking, overheating, or vibrating can cause damage to other equipment parts.

Furthermore, unexpected downtimes that stop production can create cascading financial losses that could have been avoided with a more holistic maintenance strategy. Finally, this strategy often leads to service providers focusing on fixing symptoms rather than addressing the core problem. This can mean that a part is repeatedly replaced or repaired after being worn down when the root cause of its wear could have been identified and managed before the endless repair loop even began.

PREVENTIVE MAINTENANCE (also sometimes known as 'planned maintenance') describes the strategy of implementing scheduled service tasks over a defined period of time while the equipment is still in normal operation with the intention of avoiding unexpected part breakdowns (and their extra costs) in future operation over the lifetime of a piece of equipment. In this model, equipment assets are temporarily taken off-line at predefined time intervals where predefined maintenance and replacement tasks are carried out. The main intention of a preventive maintenance strategy is the avoidance of unexpected downtimes and breakdowns with the aim of extending the lifetime of an asset while also increasing its productivity and efficiency. Filters are changed, seals are replaced, lubrication is applied, etc. at regular time intervals regardless of the actual state of the component.

Preventive maintenance models are designed to keep parts that break down from reaching the point of failure and, thereby, avoid costlier and potentially wider-reaching replacement costs.

In this sense, preventive maintenance is more cost-effective than reactive maintenance, though can sometimes be more challenging to justify to management as the initial costs of regular part replacement can potentially exceed replacement costs if parts are only replaced when they fail. As such, preventive maintenance is also based on theoretical rate of failure rather than real-life equipment performance, meaning that parts may be replaced prematurely, i.e. when they have plenty of utility and production power left to provide. Planned downtimes also can create extra costs in production loss when compared to the irregular downtimes of reactive maintenance. Studies show that preventive strategies can provide cost savings of 12-18% on average compared to reactive strategies.

PREDICTIVE MAINTENANCE (PdM) is one of the newest iterations of maintenance strategy given its reliance on the modern methods of digital technology and IIoT implementation. And yet it is one of the fastest-growing modes of maintenance strategy given its long-term financial benefits. This mode of maintenance utilizes the advancements of modern analysis (AI) derived from data provided by implemented sensors and/or historical data.

By actively monitoring performance of equipment and its many parts with comparative analytics, equipment managers can make predictions about when and where an asset will fail, thus allowing service professionals to take steps to correct an issue before it reaches the point of failure. Predictive maintenance strategies, when properly implemented, are superior to both reactive and preventive strategies in that equipment is neither run to failure (as in the former) nor are parts unnecessarily replaced (as in the latter).

Ideally, a smart predictive maintenance implementation will allow companies to make maintenance operations at the opportune time, not too early (thus wasting parts) or too late (missing root causes). A data-forward model of predictive maintenance enables a holistic overview of interconnected technologies and assets rather than a fragmented one where symptoms are repaired instead of addressing core problems. Studies have shown average cost savings of 8-12% in predictive strategies compared to preventive ones. There is plenty of evidence, however, that the upside advantages are even greater when considered over the entire life-cycle of a piece of equipment, especially in combination with an EaaS model.

Upfront investment in a well-orchestrated predictive maintenance strategy is probably the biggest barrier for companies to overcome in justifying a move to predictive methods. The costs of implementing the correct technology and training employees can dissuade some companies from considering the long-term advantages that pay back the initial investment many times over. Yet, the numbers are convincing. Independent industry studies have shown that average savings in predictive versus preventive implementation are considerable.

A report by the US Department of Energy on "Achieving Operational Efficiency" has revealed that average ROI is up to 10 times higher in predictive versus preventive measures. Reduction in maintenance costs ranges at 25-30% higher. Elimination of breakdowns is especially impressive at 70-75% higher than preventive strategies. Downtimes are shown to be reduced by 35-35% and production levels have been shown to be increased by 20-25% by using predictive methods and technologies rather than preventive ones.

Initial investment in IIoT and digital solutions can be relatively easy to justify when the long term savings in damage avoidance and minimized replacement costs are considered.

IIoT solutions that can be applied to rotating equipment, depending on requirement, include vibration measurement, temperature measurement, ultrasonic testing, power quality measurement, oil sampling, torque monitoring using strain gage technology, thermal imaging cameras and laser alignment equipment (among many others).

5. HOLISTIC SYSTEM MAINTENANCE IN ROTATING MACHINERY

As opposed to an individualistic and fragmented maintenance solution, systems experts recommend users of rotating equipment seek to create holistic service systems that enable maintenance staff to find root causes earlier and with better precision. A pump system, for one example, is operated via numerous interlinking components including elements such as pipework, impellers, pipe seals and valves, all of which depend on each other to function correctly and reliably. Depending on the installation, adverse effects such as high temperatures and thermal expansion in one component part can lead to rippling damage effects in other parts. In a pump system used in a hydrocarbon processing plant, for instance, a wide range of complex, interconnected assets need to be considered for their interdependencies rather than their singular function alone.

Mechanical reliability in rotating machinery can be best ensured by providing operators with a robust overview of the entire system and allowing users to identify potential problem areas before they develop into more serious problems in the future. In such systems, sometimes a combination of planned maintenance and predictive maintenance is the best configuration whereby essential components are continually replaced while longer-life components can be submitted to long-term analysis via sensors and IIoT installations.

The advantage of a holistic predictive maintenance solution is in its custom application. Individual components are assessed for their value in the entire chain of production and sensors are applied accordingly.

A holistic approach has been shown to ensure the maximum potential for early warning analysis and root cause identification in rotary equipment systems.

6. IIoT-BASED CONDITION MONITORING FOR AIR COMPRESSORS

Air compressors are one of the most commonly used pieces of industrial machinery and can be found in nearly every industrial sector, particularly in the oil, gas, chemical and petrochemical industries where reciprocating air compressors are commonplace. Given that such compressors often need to stay in operation around the clock without interruption, efficiency and maximum uptime is paramount. Unexpected breakdowns can be disastrous, creating not only rippling financial and production losses, but potential environmental damage and plant safety issues as well. In some scenarios, machine malfunctions have even been known to destroy entire machine trains.

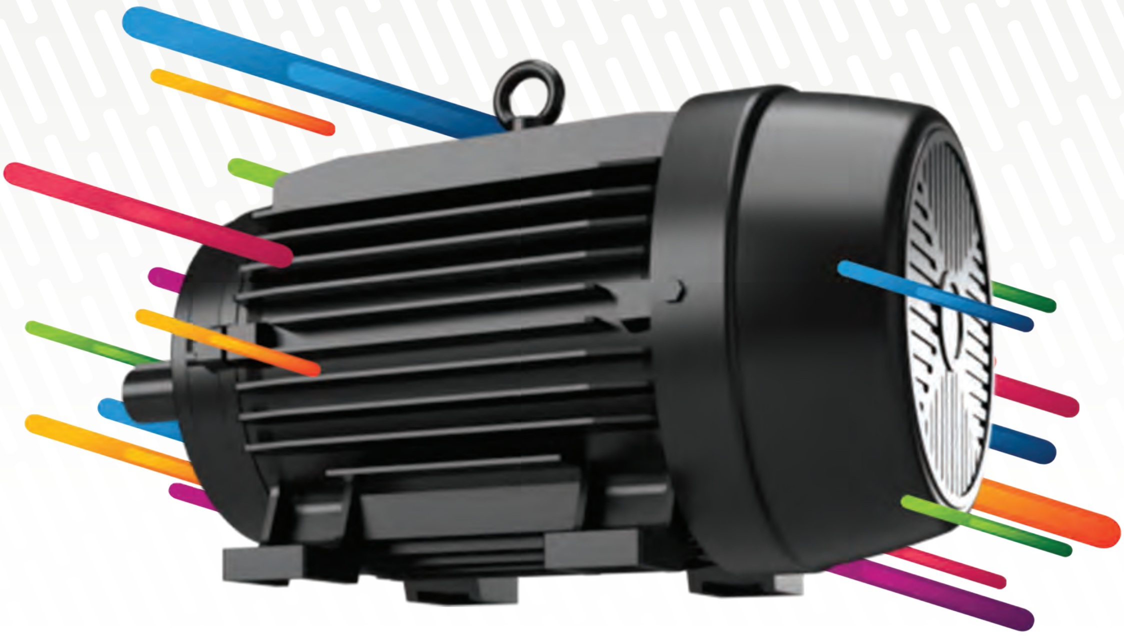
Any potential fault in a piece of equipment needs to be detected and identified as early as possible, thereby minimizing any downtime and consequent revenue loss.

The operators of air compressors can rely on condition monitoring implementation to have continual status updates of the health of compressor components and, even more importantly, isolate and predict problem areas before they turn into a breakdown. A typical reciprocating air compressor has a number of interconnecting parts where breakdowns are most likely to occur, including the bull gear, pinion gear, thrust bearing, thrust collars and compressor stage. Considering the range of applications involving air compressors, the demands placed on their individual components differ widely from plant to plant.

But nearly every application involves high levels of pressure with multiple points of potential failure. Possible disruptions, faults or failures include split shafts, misalignments, roller bearing damage, cracked blades and cavitation. Such areas include the bearing house and the foundation bed of the compressor or pump, but the sensors can be placed virtually anywhere they are required.

IIoT sensors placed throughout the compressor can measure vibration, temperature, noise, magnetic fields or any other relevant metric on these components. Sensors can be mounted anywhere that operating parameters like vibration or temperature will be fluctuating.

In a typical example, a MEMS accelerometer sensor to measure vibration might be placed near a pressure point on the compressor. The sensor would be linked to a central gateway (often by wireless internet connection) that coordinates data gathering from every other sensor on the compressor. Sophisticated data analysis of these vibration waveforms and comparison to 'normal' wave patterns allow the AI software to identify any problematic variations in vibration measurements in the wider condition monitoring system. A predictive maintenance alert would then notify operators about a potential area of concern, allowing a component to be inspected, repaired or replaced before failure occurs, thus avoiding a costly breakdown and keeping operations at peak performance.



7. IIoT-BASED CONDITION MONITORING FOR ELECTRIC MOTORS

Motors and engines are at the core of the industrial production chain. Given their role in power generation, they are at the heart of reliable machinery operation. Manufacturers who need their motors at continual operation with minimum downtime are increasingly moving from preventative maintenance to predictive maintenance solutions with the aid of IIoT sensors and artificial intelligence analysis.

Industry surveys show that over 90% of rotating machinery in industrial and commercial applications use rolling-element bearings, and in cases of electric motors the majority of failure incidents (41%) occur at the bearings.

The other major problem area in motor failure is at the stator, the element that creates the magnetic field driving the rotating armature in the motor. After bearing failure, malfunction in the stator is the largest cause of motor breakdown with 27% of failures at stator insulation and another 10% of failures defined as 'other' stator faults. Predictive maintenance (PdM) solutions are crucial to monitor the health of motor components and maximize the lifespan of an industrial motor.

Modern industrial motors are designed to work for up to 20 years at constant operation, though they often fail to run through an expected life-cycle for a number of reasons, many having to do with improper or ill-timed maintenance. Lack of investment in proper PdM implementation, in many cases, can be blamed for premature motor failure. IIoT sensors deployed correctly in a motor PdM system allow early prediction of machine faults and can help operators repair motor inefficiencies that will ultimately boost overall performance, productivity, asset availability and lifetime of a motor. Systems experts agree that the ideal PdM implementation efficiently uses as many sensors and methods as possible to analyze a motor's potential fault areas from as many angles as possible.

There are a multitude of sensors available to measure motor parameters, but a few of them include Piezo and MEMS accelerometers to measure vibration, ultrasonic microphones to measure sound pressure, shunt sensors to measure current, magnetometers to measure magnetic field, RTD sensors to measure temperature and particle sensors to measure oil quality. This array of measurements when routed through a gateway, analyzed by a predictive algorithm and displayed on a user interface provide a powerful overview of motor health and potential problem areas, allowing early failure prediction and maximum operational efficiency.

8. SERVICE STRATEGIES WITH DIGITAL TRANSFORMATION AND EAAS

Maintenance schemes in rotating machinery have continually evolved over the decades from the beginning of the industrial revolution to the modern digital era of today. Owners and operators of rotating equipment be it engines, generators, pumps, compressors, gearboxes, conveyors or any other machine with rotating parts have continually reconsidered the technology at their disposal to make sure that their equipment operates at maximum capacity with minimum downtime. Maintenance plans have thus, understandably, moved from reactive to preventive to predictive or perhaps some hybrid combination of these three schools of thought.

Asset managers have come to realize that costs over the lifecycle of a piece of machinery weigh heavily to the side of operation and service costs rather than the initial cost of the equipment itself, roughly speaking at a ratio of 20:80 with the majority side in service, depending on the machinery and its expected lifespan.

With this growing emphasis on the service and maintenance side of equipment operation, machinery operators have seen an entirely new economy open up in guaranteeing uptime and providing new analytical services for their clients. These services can be ideally provided by modern data analysis (aided by AI and machine learning) that exploits the data gathered along the IIoT/sensor array of a particular equipment setup. With data now at the core of maintenance considerations, operation has superseded ownership as the most important element in both value and financial longevity of a rotating machinery system.

As such, the service package around a piece of equipment now holds more value than the physical cost of the asset itself. This shift from ownership to operation (as part of the movement shorthand "Industry 4.0") is sometimes described as a shift in focus on expenditures from capital (CAPEX) to operating (OPEX). A new model has emerged in recent years that has seen adoption accelerate year-on-year.

This new model of service is alternately known as Equipment-as-a-Service (Eaas) or subscription model. OEMs who see the benefits and unlocked value in EaaS have been able to externalize costs around service, maintenance, operations, finance, warranties and invoicing (among other areas) as well as offer a new range of previously unavailable services to their clients. Both manufacturers and users of rotating equipment are utilizing IIoT implementation combined with digital solutions (such as system interfaces and operational analysis) to maximize uptime and minimize failure rates in their machinery operations.

The subscription model for rotating equipment has much to recommend it. Early adopters of this holistic equipment strategy are finding the digital services they can offer their clients provide them both a competitive market edge and new streams of revenue as the data-derived insights from their customized digital solutions make them more attractive to a growing client base.

The pay-per-use model and its consultative approach allows an unprecedented level of flexibility for all parties involved in the operation of rotating equipment, whether they be manufacturers, users, or service professionals.

The relayr model foregrounds IIoT implementation combined with sophisticated digital analysis to ensure that operation of rotating machinery provides maximum value to the most shareholders. The insights unlocked and service options offered by such a data-forward philosophy, says relayr, allow businesses to achieve their target financial outcomes, open new revenue streams for clients and secure overall equipment effectiveness (OEE) gains of up to 10%.

9. ONE STOP SHOP

As Equipment-as-a-Service models gain critical mass in manufacturing, there is no doubt that digital transformation becomes a stepping stone to success. When adopting digital technologies, the company's business strategy is often on the sidelines as the focus shifts to finding the best technological solution. In other words, the business should drive the technology and not vice versa. Adopting a holistic approach which encompasses business strategy, leadership commitment, talent, and strong partnerships, paves the way for a successful transformation of the entire business model.

Relayr is committed to realizing the full potential of IoT in the industrial space and covers all stages of the business transformation journey:

WE DELIVER

the most complete IIoT solutions for risk-free digital transformations.

WE UNLEASH

data insights from existing equipment and production lines to improve business outcomes.

WE ENABLE

a shift from CAPEX to OPEX based offerings by a unique combination of IIoT technology, and powerful financial and insurance offerings.

WE EMPOWER

manufacturers, operators, and service companies for industrial equipment to implement fully interoperable IIoT solutions guaranteed to achieve their business outcomes.

10. HOW WE WORK

We understand that our success only comes from your success. That's why we use a collaborative partner approach to help guide you through the challenges of your IIoT journey.

START WITH THE OUTCOME.

The first question we ask is: "What is the business problem we're trying to solve?" followed by "Can we translate this into a new significant business opportunity?". The answer to these questions will guide the entire digital transformation journey.

ONLY WHAT YOU NEED.

Because your business needs and industrial environment are unique, so too will be your IIoT solution. We work with your internal stakeholders to learn about your company's pain points and gain a full understanding of your existing industrial environment.

EXPERT LED IMPLEMENTATION.

Once your IIoT solution is agreed upon, our Professional Services team coordinates with your internal stakeholders, our technology experts and other partners to deliver a successful solution.

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