A Guidebook to Implementing Condition-Based Maintenance (CBM) Using Real-time Data

A practical guide to getting more value from real-time data by supporting effective asset management strategies

Condition Monitoring

Condition-Based Maintenance

Decision Support

Enterprise Integration

Business Intelligence

eBook

OSIsoft, LLC
1600 Alvarado Street
San Leandro, CA 94577 USA
Tel: (01) 510-297-5800
Fax: (01) 510-357-8136
Web: http://www.osisoft.com

A Guidebook to Implementing Condition-Based Maintenance (CBM) Using Real-time Data

Version: 2

Published: 1 March 2018

Contents

1 Introduction

Today, innovative asset management and reliability teams are looking for ways to use data to balance trade-offs between asset cost, performance and risk. For enterprise endeavors in particular, the challenge is to acquire, integrate and analyze data from an increasing range of operational sources without creating customized solutions. Solutions must be flexible, scalable and secure to ensure long-term viability and optimal cost savings. This guidebook provides recommendations for rapidly implementing condition-based maintenance (CBM) solutions with popular CMMS[1] applications and high fidelity asset data. The document also defines and builds on the principles of CBM to show additional business value propositions related to improving asset reliability while minimizing maintenance costs. Finally, the guidebook discusses advantages of optimizing CMMS with both real time and archived asset data using the OSIsoft PI System.

The PI System is a flexible and customizable software suite that bridges the gap between OT and IT[2] systems. Typically, our customers accelerate their ROI from various IT applications, including CBM applications, when the PI System feeds operational information from critical control systems into them. Use of the PI System results in lower total cost of ownership (TCO) solutions for operational data.

Five key advantages of the PI System support the implementation and execution of effective CBM solutions. They are:

- Extremely efficient, real time data management from a wide variety of operational sources in a highly secure manner.
- Capture and storage of streaming data at its original fidelity, without averaging or aggregating, using proven methods that scale to an enterprise.
- Embedded data directory to organize data streams and other related process information by asset and plant topology, giving the data functional and operational context.
- Easy-to-configure, advanced analytics that convert raw data streams into meaningful events and information.
- Powerful means to surface asset health information and support critical business decisions regarding asset maintenance strategies. Visualize information in a wide variety of intuitive, flexible ways, in desktop and mobile forms by users as well as other enterprise systems.

---

[1] Computerized Maintenance Management Systems (CMMS), used for work management and asset management, similar to Enterprise Asset Management (EAM) and often part of Enterprise Resource Planning (ERP) suites.
[2] OT – Operational Technology, typically the control network systems such as SCADA, DCS, and PLC, and IT – Informational Technology, typically enterprise business networks and systems such as ERP, CMMS, Customer Services, and Materials Management.

CBM can be a major component of a holistic Asset Management strategy described in internationally recognized standards such as the ISO55000 series. This guidebook presents a framework for data-driven planning and decision-making. It establishes criteria to prioritize asset management decisions according to organizational needs, defines 'value' to the enterprise, and achieves a balance when faced with conflicting objectives.

Finally, CBM and condition monitoring can mean different things to different people, companies and industry groups. Within this guidebook, we provide clarity to the most popular definitions and describe how to apply each within the PI System. Recent hype about the Internet of Things (IoT), the Industrial Internet of Things (IIoT) and advanced analytics associated with the amount of data made available by IoT and IIoT has introduced additional confusion. We hope to make it clear how to optimize all of these toward improved asset management.

2 Overview

Shifting from calendar-based to condition-based preventive maintenance (PM) strategies is a goal cited by the majority of our customers to improve asset performance, reliability and lifecycle management. CBM as a maintenance strategy crosses all major industries and asset categories (for example, rotating equipment, transformers, mining vehicles, fluid management, and so on). CBM differs from calendar-based maintenance strategies in that it leverages asset data to optimize and align preventive maintenance schedules with actual asset condition (or usage), organizational mission and changes in environment.

The CBM process starts with monitoring specific asset parameters, continues with evaluation of those in relation to limits, trends and aggregations, and ends with integration with the work management solution (for example, CMMS). Figure 1 illustrates the flow of aggregated and event-based real time data fed into a maintenance program (CMMS), along with prescribed maintenance activities. This process evolves as insights arise and system experts (asset managers, reliability engineers) apply lessons learned to the system in terms of maintenance program changes, analytics definitions, event frame analysis, and other relevant information.

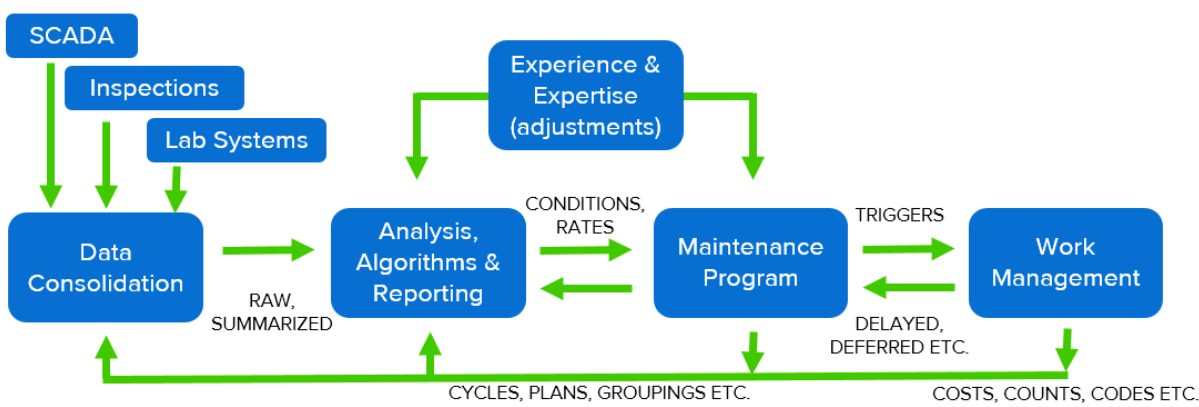


Figure 1 - CBM Is a continuous improvement process

Some common CBM scenarios include:

- Pump lubrication PM based on actual motor run-time, say 2000 hours
- Analyzer re-calibration PM based on actual drift exceeding 1%
- Filter change PM based on measured pressure differential across the filter exceeding allowable limits
- Heat-exchanger cleaning cycle PM based on calculated fouling factors

- Circuit analysis based on significant switching operations in a small amount of time (for example > 6 operations in < 24 hours)
- Transformer servicing based on dissolve gas analysis (DGA) results over time that indicate insulation degradation.
- Bearing swap out based on vibration data of motor shaft, or motor current signature analysis.

Implementing a CBM solution is a continuous improvement process, not a short-term project. You can start a CBM initiative with limited process or asset information, and diagnostic (condition monitoring) equipment is not necessarily required. This guide covers the fundamentals of CBM, including how it differs from other strategies such as reactive or model-driven. It includes steps to get started with CBM and illustrates advantages of using real-time, high-fidelity asset data to maximize the value of a CBM implementation.

The guide also covers typical architectural configurations from the very simple to the very complex. We introduce the PI System, its major components and describe how to use them for CBM. We also cover how to integrate PI System data (time-series) with enterprise applications such as CMMS. We provide some input toward building a business case for CBM and lessons learned from previous implementations of diverse CBM solutions. Several examples using common asset types are included to show benefits and value across industries.

In this guidebook, we discuss the following topics:

- Condition Monitoring
- Condition Based Maintenance
- CBM design
- CBM monitoring and analysis
- CBM extension and tools summary
- Basic PI System Overview
- PI System integration to external systems (such as EAM and CMMS)
- Enabling Opportunities – What else does a CBM project enable?
- CBM with PI implementation options
- Business Value and Reference Examples

2.1 An Introduction to Condition-Based Maintenance (CBM)

2.1.1 Definition

Condition Based Maintenance (CBM) is a set of maintenance processes driven by real-time asset information to ensure maintenance is performed only when evidence of need exists. CBM can also be useful in fault prevention by recognizing equipment degradation before catastrophic failure occurs. There are other more specific examples, and we discuss those in depth in the remainder of this section.

Most CMMS applications support integration of OT (Operational Technology) time-series data via the concept of a meter (or counter). A meter is either quantitative or qualitative. Quantitative meters are used for numerical quantities such as run hours, temperature, rate of change, material processed, fouling factor in percent, and time (in seconds) to transition. The CMMS can generate prescriptive maintenance (such as a PM task, or a repair and replace order) when specific numbers are exceeded. Most CMMS systems can also forecast when a trigger point will occur based on the pattern of change sent to the CMMS by the PI System. This is useful in generating orders in time to plan and schedule them appropriately.

Qualitative meters are those that are setup to maintain states, such as “good” and “bad”, or the street light example of “red”, “yellow” and “green”. For one or more of the states, the CMMS can also generate a prescriptive order or work notification.

The integration of OT data with CMMS via meters is intended to drive preventive maintenance (more effectively than on calendar basis alone), and corrective maintenance when CBM detects an incipient failure or some abnormal condition exists.

In addition to the above, we often hear operational, reliability and maintenance personnel say they want to know “when the system is not operating as it normally does”. This is also known as “anomaly detection”, and is the most prevalent and valuable “advanced analytic” applied in condition monitoring scenarios. The technique used to detect anomalies is Advanced Pattern Recognition (APR). There are a few statistical algorithms well suited to APR and a number of OSIsoft partners that offer solutions with the PI System for APR.

2.1.2 Objectives

The goal of a CBM implementation is to move from a strictly *calendar*-based preventive maintenance program to a *condition*-based preventive maintenance (PM) program. This will mean that PM tasks are scheduled based on usage or asset condition (quantitative and qualitative, respectively) and not only on time. This is the most prevalent definition of CBM, although often confused with other “condition monitoring” scenarios that all fall under the CBM moniker.

It is important to realize that moving PM tasks from exclusively time-based scheduling to a schedule based on asset usage (for example, run hours or start/stop counts), or asset condition (high vibration) results in significant cost savings. While a relatively simple implementation in most cases, it is extremely valuable. If you have not started with this approach and are considering some "advanced analytics" solution, consider improving PMs first, as it typically results in the most significant cost savings.

The main objectives of CBM are to:

- Reduce maintenance costs (stretch maintenance cycles)
- Reduce adverse impacts of maintenance activities (if it works, don't fix it)
- Improve asset reliability (ensure assets are functional and capable)
- Improve asset availability (minimize asset downtime)
- Enable value realization from condition information (for example, lifecycle extension, decision support, and better capital expenditures)

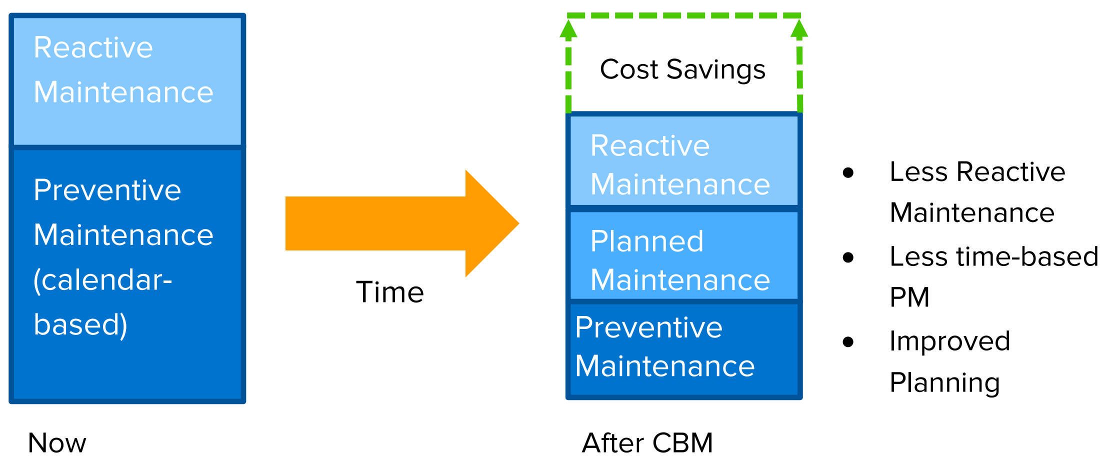


Figure 2 - Cost and Maintenance Distribution before and after CBM

2.1.3 Role of CBM in CMMS

Maintenance processes are normally managed in a work management system as prescribed maintenance tasks (preventive or planned). Work management systems such as CMMS may be a complete and dedicated piece of software or a module of a more comprehensive enterprise asset management (EAM) or enterprise resource planning (ERP) suite.

Preventive Maintenance (PM) processes are traditionally based on calendar (time-based) schedules due to a lack of asset-specific condition information. Calendar-based schedules are more conservative and occur more frequently to avoid running an asset to failure. Because calendar-based schedules can generate unneeded maintenance, they can increase costs as well as damage to assets during unnecessary repairs and decrease overall asset availability.

When asset information is integrated into a CMMS, maintenance processes are generated by asset-specific condition indicators that predict when an asset *needs* scheduled maintenance. These indicators are often supplemented by a calendar schedule to ensure maintenance is performed even when the asset is little used. A familiar example may be oil and filter replacement of a vehicle, which is typically stated in terms of a condition (7,500 miles driven) or a calendar event (6 months duration), whichever comes first.

EXAMPLE: Modern vehicles can detect the condition of the lubricating oil in terms of effectiveness (expressed in %) and recommend replacement when the oil is losing its effectiveness.

EXAMPLE: A compressor needs maintenance after a certain number of start/stop cycles. If start/stop cycles cannot be counted, conservative factors would be used to estimate a time interval after which maintenance should be scheduled. The factors could be based on predictive information or vendor recommendations to ensure maintenance happens before exceeding the recommended number of cycles. In contrast, CBM ensures maintenance happens only when a need exists. CBM gives the advantage of setting maintenance cycles at longer periods than would be using conservatively based time schedules, thereby saving money and increasing equipment availability.

Real-time asset information enables users to define asset-specific condition indicators from raw sensor data or though data calculation. Condition indicators derived from asset data initiate maintenance tasks based on real time conditions and are asset-specific. Real time asset data may come from on-line monitoring (temperatures, delta pressures, start/stop sequences), off-line diagnostic tests (eddy current, corrosion inspection, oil analysis) or portable test equipment (thermography, electrical test sets) The PI System can manage, historize (collect and store over time), aggregate and analyze on all of these data types with information from other sources.

The benefits of well-implemented CBM programs extend beyond strictly lowering PM costs. When real-time asset data provides visibility into the condition of assets, maintenance schedules and costs are optimized (will that compressor make it until the next outage?). Common failures or issues that occur across units or within fleets can be identified (why is maintenance more expensive on a specific vendor's equipment compared to other vendors?). Just by creating visibility into asset condition indicators, data can help prevent catastrophic failures. Typically, it only takes a few big saves to pay for a complete CBM implementation.

2.2 Maintenance Strategies

The following section provides information on terms that often arise when discussing CBM solutions. These definitions are in the context of this document and not exhaustive. Note that there is no standards organization to fully govern them; these are industry terms.

Maintenance strategies describe an organization's approach to maintenance for a given group of assets. Often these strategies are characterized as a maturity model, although it is not always necessary to use advanced techniques on all asset types. In practice, most organizations apply a combination of these strategies to their asset fleet dependent on asset criticality, impact of failures to the business, costs and other factors. Techniques such as FEMA (Failure Modes and Effects Analyses) and PM Optimization studies often help in determining the correct approach.

Figure 3 is an illustration comparing various maintenance strategies in terms of efficiency and effectiveness. Although the figure shows model-based (Predictive) as the most effective and efficient. However, it is not always the most valuable, nor appropriate for all equipment and systems. The figure also shows reactive as the least efficient and effective. However, a reactive strategy is appropriate for some equipment depending on the cost to repair and the impact of the loss of its function.

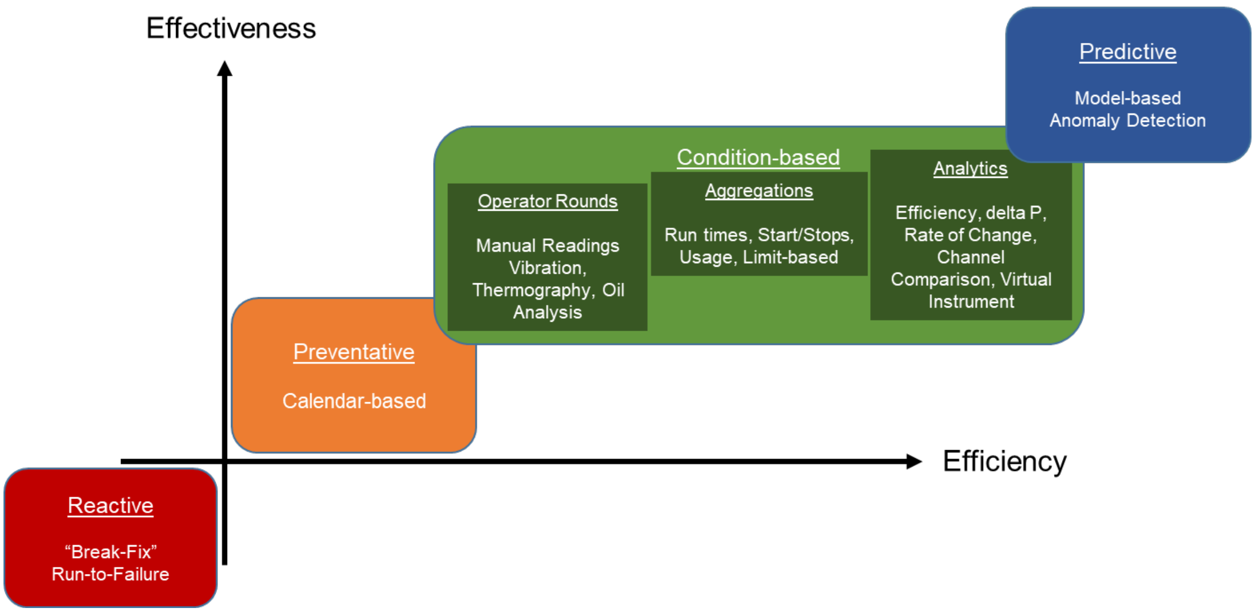


Figure 3 - Maintenance Strategies by Effectiveness and Efficiency

Reactive Maintenance

This is a "run to failure" strategy, appropriate for some non-critical assets when impacts and costs of failure are minimum. It requires a minimum of setup and oversight in terms of inputs such as manpower and specialized equipment. Usually when we select reactive maintenance for an asset or asset group there is also no preventive maintenance performed on the assets. The decision is to let the equipment run until it experiences a failure and then perform corrective (reactive) maintenance.

Preventative Maintenance

This approach includes calendar-based preventive maintenance, and corrective maintenance in response to incipient (or catastrophic) failures. The strategy requires periodic asset maintenance such as lubrication, oil replacement, filter checks, diagnostic checks (thermography, eddy current testing), and often requires that the asset or system be taken off line (or out of service). This is a conservative maintenance process, that can sometimes lead to induced failures but is often the only means to maintain the asset.

CONDITION-BASED MAINTENANCE

This approach is generally applied to a set of critical assets, or those assets that have significant repair and replacement costs, or cause significant impacts to the business process when they fail. Specialized condition monitoring equipment may be required to track the condition of assets and respond to trends or events that indicate a degraded condition. However, in most cases we can derive indicators of equipment condition based on operational data alone, such as run hours, start stops, time to transition or operate, excessive temperature and delta pressures across a screen or filter. In addition, simply calculating the asset or system's efficiency or performance is very valuable.

We highly recommend that you start with the data you have and see what the PI System can derive before deploying specialized sensors for condition monitoring.

MODEL DRIVEN MONITORING (ADVANCED PATTERN RECOGNITION OR APR)

Model driven monitoring is both a maintenance and operations approach to reliability and improved operations. This approach requires that an anticipated operational model exist for the asset, system, or process for a given set of ambient and input values. Operational models are based on previous experience of a similar plant or system to forecast expected behavior given current conditions. Sometimes, model driven approaches are referred to as "Predictive".

The model provides anticipated values for process parameters (for example, temperatures, pressures, vibration). It is extremely effective in answering the question "I want to know when the system is <u>not</u> operating as it has in the past" -- also referred to as "anomaly detection". Advanced Pattern Recognition (APR) is a common name for this in some industries. Several statistical techniques have proven very effective with APR, and OSIsoft has many partners that offer APR with the PI System.

This method requires two steps: one to set up the model (based on asset or system history) and another to "operationalize" the model (monitor the asset or system in real time). In the latter step, real time sensor values (actual values) are compared to anticipated values. Identified deltas (discrepancies) provide awareness of unanticipated asset condition or operational anomaly). In typical use, analytics periodically checks a monitored parameter to ensure that it is within anticipated range. Analytics triggers an alarm when consecutive samples all indicate that the monitored parameter is outside anticipated range, based on configuration.

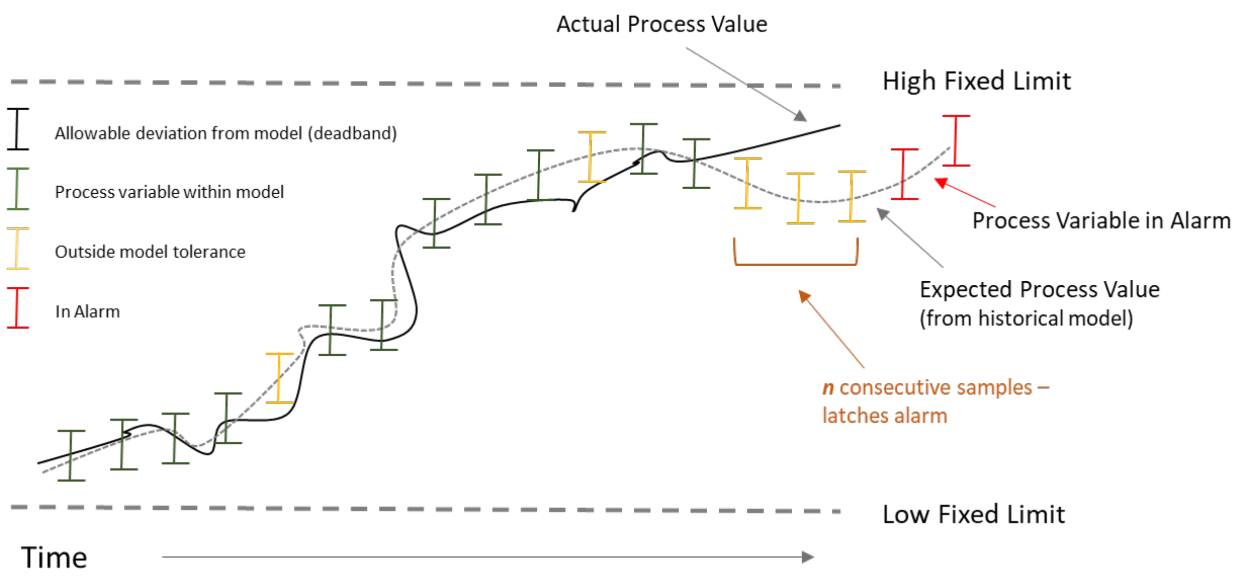


Figure 4 - Example of APR in action on a monitored process variable

This approach is complex, although you can start small with focus on critical parameters and then grow them into a model for a complete process or plant. Industry groups such as EPRI, standards organizations such as IEEE, and OEM companies often offer models for specific assets and systems. You can also start with one critical system or component and expand to others over time.

These techniques are extremely effective in detecting abnormal (anomalous) operational conditions. Anomalies need to be evaluated to determine whether the asset is beginning to fail, the model needs to be updated, the system is being operated differently than before, or the anomaly is due to some other factor. By current industry estimates, the tuning of the model results in false positives for about 4 of 5 anomalies detected. It is important to evaluate an anomaly quickly to determine the cause, and this is where the PI System excels.

The approach is based on the concept that as a component is beginning to fail, it will exhibit behaviors in data signatures that indicate an anomaly. This is also referred to as “incipient failure detection” as the failure will appear very high on the P-F curve, and well before functional failure (see Figure 6 for more information on the P-F curve). Keep in mind that this also means the equipment is starting to exhibit damage, which results in the data signature showing the anomaly (for example, the bearing could begin to score the race).

In any case, expect a fair amount of expertise and time to be spent on setting up and maintaining this approach.

RELIABILITY CENTRED MAINTENANCE (RCM)

Reliability Centered Maintenance (RCM) is a maintenance philosophy involving many techniques, methods and processes that attempt to maximize reliability of components, systems and units. It can include spare parts programs, maintenance training and implementation of CBM. This approach is driven by similar pressures that lead to the need for CBM as a maintenance strategy.

Figure 5 - Drivers for Reliability Centered Maintenance

Asset owners often employ RCM in cases of extremely volatile or risky endeavors, although it is very effective in any process industry. For example, nuclear power generation, the aviation industry and critical chemical processes often employ RCM as a part of their maintenance strategy.

2.3 Maintenance Types

PREVENTIVE MAINTENANCE

Preventative maintenance (PM) is proactive and assumes that no equipment failure has occurred. Historically, this has been based on calendar or facility events (for example, regularly scheduled outages), and not on condition. Not all assets necessarily have preventive maintenance plans. The decision employ PM options is often determined by a review of cost versus value during a PM optimization effort.

PM is prescriptive and characterized by pre-defined tasks that are performed to accomplish the specific preventive maintenance activity. They generally follow a vendor (or OEM) recommendation, regulatory guidance and industry experience.

Planned Maintenance

Planned maintenance activities are very similar to preventive maintenance, and the terms are often used interchangeably. These activities are prescriptive and follow recommendations. However, they are generally also referred to as event-based, and called for after a specific event such as a predictive indicator. Preventive maintenance is included in the planned category. Repair and replace work is an example of a planned maintenance order.

Corrective Maintenance

These activities are reactive in response to an asset problem or failure. Except for run-to-failure components, corrective maintenance activities are minimized in most cases due to their cost and impact to operating conditions. Such tasks typically include “inspection” or “troubleshooting”.

Incipient failure detection and repair is one type of corrective maintenance, and occurs when either a diagnostic measure (such as vibration or thermography) or a model (such as APR) has detected an abnormal condition. The condition may represent the early stages of asset or system failure, which is explained further in the following section.

Predictive Maintenance

Predictive maintenance uses condition monitoring and other stochastic methods to determine when a failure will occur, or to predict the useful remaining life of an asset. Other approaches use diagnostic measures such as vibration, thermography or oil analysis. In still others, models are employed for anomaly detection or APR. Overall, the goal is to remove the asset from service before full functional failure occurs. Some predictive techniques require that the asset be removed from service prior to application. Examples are eddy current testing of shell side tubes in a heat exchanger, or electrical tests of windings of a motor or transformer.

Consider that in this case that incipient failure has begun. Any further operation continues to damage the equipment and so it is important to determine quickly the remaining time until full functional failure.

The predictive maintenance model uses various techniques to produce a point on a graph to determine the remaining life of an asset. The graph is referred to as the P-F curve. This curve plots asset condition relative to time, with the idea that the earlier the condition can be detected (the P point of the curve), the more time remains available before full functional failure (the F point on the curve).

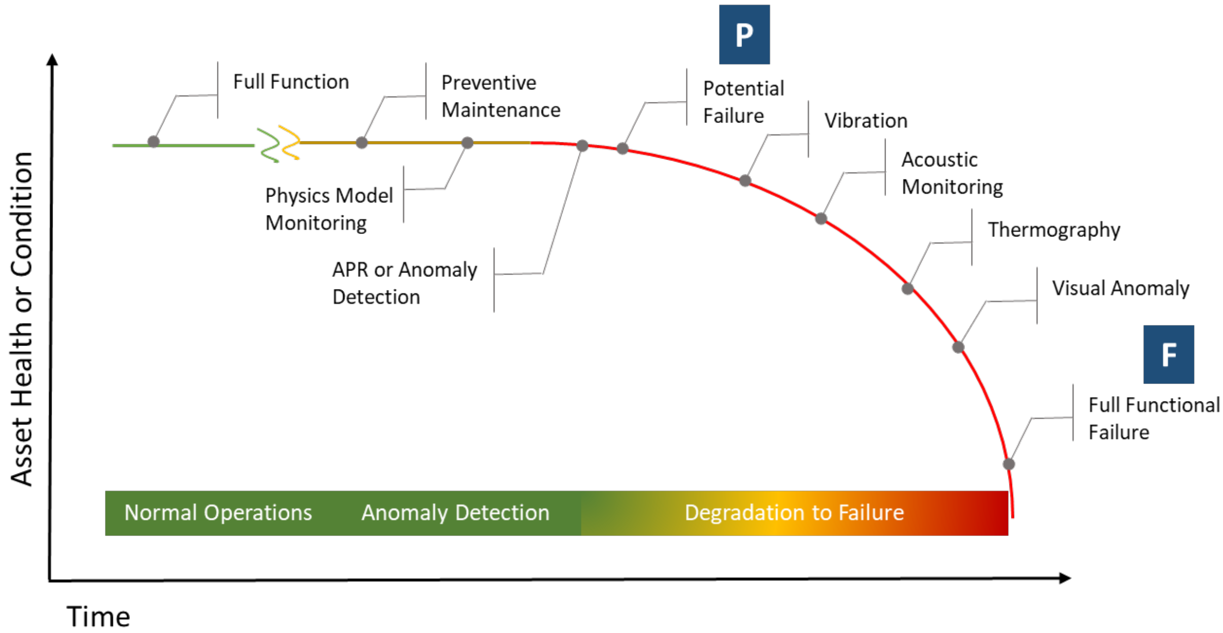


Figure 6 - PF Curve used in Predictive Maintenance (or Incipient Failure Detection)

The time between the P point (Potential failure) and the F point (Full Functional failure) determines the response opportunity time. This period varies based on asset, type of test, test result, failure mode and frequency of the testing method. Often there is little time to respond, depending on plant conditions, time of the notification, and so on. Most commonly, alarms for critical items are sent to Operations to ensure equipment can be moved into a safe condition prior to catastrophic failure.

3 Implementing CBM

This section contains practical advice on starting a CBM initiative for your organization. CBM initiatives tend to be journeys rather than projects. CBM is best implemented as a continuous improvement effort. They typically start small and expand over time as process and information becomes more refined. Treating CBM as a project will often doom efforts from the start. Full CBM often involves a cross-disciplinary group of people; in many cases assembling and organizing an effective team can be the main challenge to expedient CBM implementation. Internationally recognized standards such as ISO 55001 and PAS 55 reinforce the idea that successful programs require participation from all organizational levels and alignment to core business missions.

Note that specialized condition monitoring equipment is not necessary to start most CBM initiatives. This equipment does provide benefits for specific assets and failure modes but is often expensive to install and may require specialized skills to interpret data. Specialized condition monitoring equipment can also create separate user interfaces, notification methods, and integration paths to CMMS, which tend to compete with common enterprise goals to consolidate systems, interfaces and integration paths. Carefully weigh the costs against the benefits of specialized condition monitoring equipment, to determine if it is justifiable. It is often beneficial to start first with the data you have and use that as a basis to justify further investments.

It is possible to interface condition monitoring equipment using the PI System to create one user interface, one integration path to CMMS, one notification system, and one source of condition monitoring data. OSIsoft has a number of partners that offer solutions that are relatively simple and less expensive to implement to test out specialized condition monitoring equipment.

3.1 Building a business case

Quite often developing justification to pursue CBM initiatives is already well understood by the business. If not, there are some excellent references available to discuss how CBM can lower maintenance costs, reduce lost opportunity (periods where assets are unavailable), collateral damage and redundancy costs. Two issues typically compound movement forward:

1. Everyone is too busy – These initiatives take a fair amount of resources from a wide variety of disciplines. They change the way work and often operations are accomplished and require IT and OT work to tie systems together. While often perceived as a lack of leadership, most people are actually too busy doing day-to-day work to take the time to gather, align, define goals, and acquire funding required to launch a CBM initiative.
2. CBM as a project instead of continuous improvement – CBM is most successful when implemented as an organizational change. CBM does require some upfront investment, but organizations do not need to address all CBM needs in one project. It is best to start CBM as a small project with the understanding that the implementation will continue to iterate and evolve.

Considering the two caveats above, we find the most success when we can work with customers and partners to help them identify significant and quick wins. The wins can result in measurable cost savings and usually suffice to develop ROI for the initial project and change management.

Having details specific to your industry on where others have identified substantial savings can help build a solid business case, and is often a good starting point. This data can help scope, charter, socialize and plan the initial project based on specific assets. Consider any expensive, impactful maintenance events in the last year and if CBM could reduce 20 – 50% of them, it is usually justified on that basis alone.

When considering events for cost/benefit analysis, include not only the replacement cost (parts and labor), but also the additional costs of impact to the business, risks incurred, and other impacts (environmental, health and human safety) for a full assessment of benefit.

3.2 Getting Started

In this section, we break out two major areas for consideration. First, we speak to the need to identify assets to include in the scope of a CBM initiative. Second, we outline a recommended process that has led to successful initiatives in the past. These two factors facilitate a process to start, grow and mature a CBM initiative. Keep in mind that CBM is a journey, not a destination; it will take some time to mature CBM within an organization.

3.2.1 Identification

A focus on getting started is vital to developing a successful CBM implementation. Begin by identifying some asset candidates for CBM. They should be assets that are currently serviced through calendar-based schedules and would benefit by converting to CBM. Some sources of information to help identify equipment that may be best candidates include:

- Criticality to process – CBM is particularly relevant when assets are critical to process. Identifying single points of failure within a process can help select assets that would deliver the most value if monitored with CBM.
- Maintenance history – History helps to identify assets whose mean time to repair (MTTR) or mean time between failures (MTBF) are out of prescribed ranges.
- Strong business case (ROI) – When cost per failure is high for particular assets, targeting these assets for CBM presents a strong financial return.

After identifying asset candidates for CBM, use the following resources to further identify candidates for the pilot implementation:

- Failure Modes and Effects Analysis (FMEA) reports – These reports Identify how a system may fail and the effects of failure. Especially for large or critical systems, FMEA reports should contain indicators of failure methods which may identify key points for condition monitoring. From the FMEA, develop control strategies for each failure mode and include a preventive task, a predictive task or an operator task. Then, combine these tasks to form the basis of a maintenance plan.
- Root Cause of Failure (RCF) or Root Cause Analysis (RCA) reports - are post incident reports that show how smaller issues and their ability to go undetected can result in a major incident. Identify potential sources for condition monitoring by identifying missing or non-alerted conditions in these reports. RCA and RCF is greatly enhanced by easy, intuitive access to long-term archives of real time, condition and other data related to the asset. This is a primary function of a PI System.
- Subject Matter Experts (SMEs) – SMEs are aware of the equipment that could be monitored for CBM and will help in determining how to use available information to determine asset condition. They are also vital in getting new instrumentation to help with condition monitoring.
- Maintenance planners – Depending on the type and size of the organization, maintenance planning may be a dedicated function. These individuals are usually involved in putting together calendar-based preventative maintenance and will likely know where vendors recommend condition-based over calendar-based maintenance. Maintenance planners will also be necessary to set the configuration of CMMS to support CBM.
- Industry references and vendor manuals – These are great resources to find vendor recommendations on maintenance and define condition-based requirements. Industry references illustrate incidents from many similar plants in your industry where correctly applying CBM returns the most value. They can be helpful in putting together the condition parameters and any necessary combinatorial parameters.

Technology is not typically the limiting factor when operational data management systems such as the PI System are present. In our experience, technology is typically less of a challenge than overcoming the organizational issues associated with establishing a CBM solution.

3.2.2 Implementation

OSIsoft recommends organizations consider the following steps as an initial implementation process, following a crawl, walk, run model toward maturity. Organizations often struggle for many reasons when trying to get to the mature phase in a single step. CBM involves changing the conduct of asset management and maintenance processes. These changes can affect a wide variety of people within an organization and incremental steps are usually most effective:

- Basic usage statistics and aggregation
- Condition monitoring on physics-based models
- Model driven monitoring, or APR
- PM changes using condition information
- Fully integrated work process models

3.2.2.1 Basic Usage Statistics and Aggregation

The first step is to consider basic metrics of equipment usage such as run hours, start/stop cycle counts, material processed, or equipment travel time. Often the PI System can establish metrics without needing specific instrumentation. For example, customers often use breaker or equipment state to determine run times or start/stop counts. Time between "fully open" and "fully closed" states can be used to determine valve stroke time.

While it is common to aggregate this information over the lifetime of the asset, it is also valuable to monitor these metrics by period. For example, it may be useful to look at pump run times by "month to date" or since the last maintenance activity. These are easy to configure within the PI System and do not require additional tags or data streams.

3.2.2.2 Condition Monitoring on Physics Based Models

The next step is to think beyond the simple component and consider the larger system or subsystem. Some typical examples include efficiency, fouling factors, delta pressure across a screen or filter, and instrumentation comparisons.

Pumps, turbines, compressors and cooling towers all have efficiency calculations that can be computed and monitored over time for unexpected changes or "out of tolerance" conditions.

If there are multiple instrument channels, or the ability to create virtual instruments through related parameters, you can compare an individual instrument to validate it over time.

Most PI System customers are involved in asset-intensive process industries. Equipment in process industries is arranged in engineered systems to perform specific functions. Each system or process can be monitored for efficiency and other critical metrics.

3.2.2.3 Model Driven Monitoring or Advanced Pattern Recognition (APR)

Model driven monitoring (primarily APR) is extremely effective for anomaly detection. The primary human interaction is to quickly assess the anomaly to determine if there is a real issue, where it is, and the failure mode. The PI System can capture the anomaly as an event and provide a notification to a subject matter expert (SME) for follow-up analysis. PI Vision makes it extremely easy to review the event and process data relative to the asset and over its entire history. The SME can then capture the result of the analysis in an event frame.

OSIsoft has many partners that can implement APR as an application with the PI System.

3.2.2.4 Preventive Maintenance Changes Using Condition Information

At this stage, we build on the previous experiences and integrate information in the PI System with CMMS. The condition and usage information is integrated into a CMMS to drive preventive maintenance (PM) tasks directly. By this time we should have confidence in the analyses set up previously, and that the integration is performed with the right number of transactions, or on the right periodicity. Nothing hurts CBM's reputation within an organization more than overloading another system with meaningless information or failing to send a critical update.

The changing of PM tasks from calendar-based to condition-based and usage-based is not technically challenging in most cases. But it is often most challenging from an organizational perspective. To fully setup PM tasks to be driven from conditions, it often takes many different roles within an organization to come together in pursuit of common outcomes. This includes IT and OT technology, reliability engineering, planners/schedulers, maintenance personnel, and operations.

3.2.2.5 Fully Integrated Work Process Models

At this stage, we build on previous integration work to offer a more informative work experience in other systems and work processes. For example, you will want to expose condition information in CMMS for purposes other than strictly driving PM tasks. You may wish to provide information by asset type to asset displays to enable the end user to see real time data with both the work order history and asset details.

You may also want to expose condition information in other IT platforms such as Geographical Information Systems (GIS), engineering applications and operations platforms. These integration efforts often take advantage of PI System integration technologies, such as the PI Integrator for ESRI ArcGIS, and are often much more technically complex than integration to drive PMs with condition data.

3.3 Condition Monitoring

Once you identify suitable candidates to pilot CBM, it is important to discover and refine information that will guide the process. Condition monitoring is the process of using asset data to monitor a parameter (such as vibration or temperature) to identify an indicator that predicts a developing fault. It is a major component of predictive maintenance, and a necessary predecessor to CBM. Condition monitoring often involves unique and innovative ways to use data to develop accurate indicators of asset health. Some form of condition monitoring, however basic, must be performed in order to send updates (or transactions) to a CMMS when CBM is fully implemented.

Condition monitoring could be as simple as recording operator rounds (by shift, weekly, monthly, and so on) or collecting hour-meter readings, or calculating equipment efficiency or quite complex. For example, one can run Fast Fourier Transforms (FFT) on current and voltage waveforms of transformer windings and analyze harmonics to detect issues. The results could be a state value (indication of an issue) or an analog value. The analog value could be monitored separately and used in many ways, including updates to CMMS.

Sometimes condition monitoring involves specialized equipment that looks at a certain aspect of an asset to understand a degradation metric such as vibration, acoustic monitoring or oil analysis. Depending on whether specialized equipment is involved, the results or indication of the condition may only be available using dashboards, displays and/or reports.

The main difference between condition monitoring and CBM is that CBM involves the integration of condition data with CMMS to drive maintenance activities. Condition monitoring is a prelude to CBM. We recommend starting with condition monitoring alone to test the ideas and concepts behind CBM rules before integrating them with a CMMS.

Sometimes condition monitoring involves existing process variables and typically aggregates them to determine asset health relative to other assets within and among peer groups. We refer to this as "condition assessment."

3.4 Condition Assessment

Condition assessment (CA) is the aggregation, assimilation and normalization of a series of condition indicators or factors related to an asset. The result is an overall condition indicator (or asset health indicator) in a range or state. This indicator of one asset is then compared to the score of others in the same peer group. In the most extensive definition of CA, the condition indicator is normalized to the point that it can be applied across peer groups and be rolled up through an asset hierarchy, allowing system-, unit-, plant-, and fleet-wide comparisons. CA helps prioritize capital replacement and improvement dollars, system engineering time or maintenance prioritization.

Condition assessment often makes use of data other than performance data. This often includes maintenance process data such as Mean Time Between Failures (MTBF), Mean Time To Repair (MTTR), asset criticality, CM/PM ratios (costs or counts), recent trends of damage, and cause codes.

It may also include nameplate and other static data such as age, manufacturer, grade, and cost to replace. These factors are often valuable as recent values and historical trends. These data, as well as condition indicators, come from the CMMS.

To develop a condition assessment indicator, we first define factors for the equipment peer group. These factors are limited to data availability; you cannot use the gas content of a transformer's oil tank if it is not available. If data is available for some factors and not others, you will need a default or typical value when data is not available. The condition assessment (CA) is a sum of the individual factors:

$CA = F_1*M_1 + F_2*M_2 + F_3*M_3 + F_4*M_4 + F_5*M_5...$

where

M is a number between 0 and 1 and $\sum_M = 1$

and

F is a number between 0 and 10

For each of the factors, develop a case statement to compare the actual condition indicator to a set of values and determine a numeric result between 0 and 10. You can determine whether you prefer 0 or 10 to be good or bad, based on the evaluation of the case statement. Providing a default or typical value for missing data is a good practice.

The condition assessment algorithm should be specific to the asset peer group and applied periodically to each asset within the peer group. The result (CA and each factor) should be historized to provide the ability to associate an asset with its CA and trend the corresponding values.

The CA value can be used with CBM for qualitative assessment. For example, 0-2 creates a maintenance order based on maintenance plan *x*.

The results also provide current and historical values for the condition of the asset that is useful in capital replacement determination, work prioritization and system health assessments. Asset criticality can also be included to create more risk-informed models that drive maintenance decisions.

3.5 CBM Configuration (Maintenance Plans)

CBM configuration is primarily done within the CMMS where the maintenance processes (plans, tasks and strategies) are configured. Calendar-based maintenance relies on time-based configurations. For CBM we configure maintenance processes on asset conditions. Instead of using a clock (time-based) we use a meter or measurement point where a condition is recorded. Remember that CMMS that support CBM use a meter to trigger pre-defined maintenance plans, even if the plan is simply to investigate the cause of the condition. The configuration of the maintenance plan will typically include calendar-based input as well. This concept is analogous to changing the oil in your car every 7,500 miles or 6 months, whichever comes first.

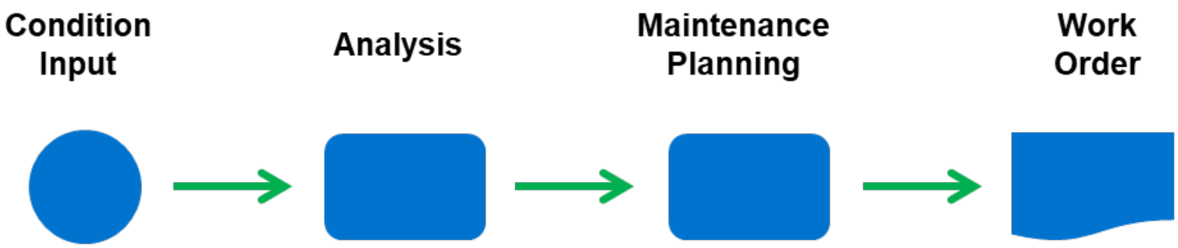


Figure 7 - Simplistic flow of condition-driven maintenance process

The meter's current and previous values are used by the CMMS preventive maintenance program to predict when maintenance should be performed. To optimize CBM implementation it is always important to avoid these two scenarios:

- Generating too many unnecessary maintenance items within CMMS – This can result in a reluctance for maintenance to take orders seriously because the system overwhelms them with "noise." Systematically removing false positives is key to broad adoption and realizing maximum benefit by focusing attention only when it is truly needed.
- Missing a necessary maintenance order -- If a critical asset fails based on its condition and that indicator was not passed to CMMS. The impact to the plant or process could be significant.

It is imperative to operate or test the logic of a condition monitoring process that intends to send automated transactions to CMMS. This should be done over a specific period or the entire history (of PI System data) to ensure that a level of confidence is established when the process is automated.

A computational task or job must be scheduled within the CMMS to compare recent meter history and develop forecast dates for work order generation and scheduling. This is much like the jobs run for calendar-based maintenance which consist of lead time for order generation. Since the lead time for CBM is based on the progression of meter data and not days transpired, the lead time generation calculations are more complex.

This job should be scheduled at typically once or twice the frequency of anticipated meter updates to ensure events are not missed. The creation of the work order is determined by parameters defined within the maintenance plan (such as lead time) and considered by the preventive maintenance program. In other words, the order may be created many days or even weeks ahead of the anticipated need time of the maintenance to ensure that there is adequate time for planning and parts procurement. Since the maintenance planning job runs daily, sending measurement updates more than once a day is usually unnecessary. Consider these settings carefully.

3.6 Quantitative-based meters (count)

Meters are defined in one of two ways, either quantitative (usage or counter-based) or qualitative (state or characteristic-based).

Quantitative-based meters represent numerical values that typically move in one direction (or count). These values are often subcategorized into two counting types: usage and events.

Usage counting generally refers to a summing of time, material or flow. Examples may include compressor run-hours, board feet produced or kilowatt hours (kWh) used.

Event counting refers to discrete events. Examples include breaker operations and start/stop cycles. To use a recent airline example, the compression and decompression cycles of certain 737 jets have been limited to a fixed number before a manual inspection must occur. The compression cycle event is a typical flight for a 737 (take-off, compression, landing, decompress).

Quantitative-based meters are used most often in predictive cycles. They have the greatest impact in determining when a CMMS will create a preventive maintenance order.

Here are some special considerations to keep in mind when establishing meters:

1. Since meters generally run from 0 (or their previous value) to current value, consider resetting the start value within the CMMS for the next scheduled maintenance once maintenance is complete.
2. We often need to consider the significant digits of the meter. Meters will roll over at some point based on their characteristics.
3. When the source instrument fails, and if the initial value of the replacement instrument is set to some other value than the last value of the failed instrument, there may be a need to adjust the value in the CMMS. An alternative is to offset the value before sending to the CMMS, which can be done using the PI System.
4. There may be times where counter operations are incurred at the meter (or conditioning algorithm) that should not be factored into the need to do maintenance. In these cases either the CMMS meter readings will need to be manually adjusted or an offset value implemented before sending to the CMMS (which can be done in the PI System).
5. When sending information to the CMMS from the PI System, ensure either the delta reading (value for the last period or value to add to existing meter) or the new meter reading is sent. There are pros and cons to consider for each asset class.

3.7 Qualitative-based meters (state)

Qualitative-based meters consist of two or more discrete state values and reset to a new value through a meter update. The discrete values within qualitative meters generally represent the improvement or decline in the health of an asset's condition. State values generally require that calculations are performed on primary asset data to determine the current condition of an asset.

It may be helpful to think of a qualitative-based meter as a traffic light with green, yellow and red colors. When calculated data indicate that there is a defined state change, a meter update is sent to CMMS. The CMMS informs the maintenance plan based on the input.

EXAMPLE: Some oil analysis systems collect a lot of detail about water and gas content of the oil and use either industry standard or proprietary algorithms to convert this information into four states. These states indicate progressive health conditions while hiding the details of the cause of the issue. Using these states to plan work in CMMS is a good example of a state-based meter. Based on the state of oil health, the maintenance process may be dictated using previously defined tasks.

Here are some special considerations to keep in mind when establishing meters:

1. An assessment algorithm should not run more than once between cycles of the CMMS maintenance process. State changes could be missed if the condition was close to becoming a worse state. An alternative is to have the condition algorithm monitor and account for this chatter.
2. Extreme state changes may occur for a variety of reasons and should be properly planned for in the maintenance planning process. There may be a need to combine these meter updates to the CMMS with an immediate notification for maintenance.
3. State changes in the condition of an asset may occur during routine maintenance of that asset for an unrelated cause. Special precautions need to be planned for to prevent unnecessary and noisy order generation when irrelevant.

3.8 Immediate Maintenance Order Generation

Aside from using meters and pre-defined plans, new work orders may be generated based on established limits, which can be set up in the PI System. In such a case, established limits need to be integrated with the CMMS to initiate an immediate maintenance order. A Maintenance Planner determines specifics for the order and instructions for carrying it out before assigning it to the field.

Immediate maintenance order generation is a relatively simple integration to set up. The specific scenarios are the same whether doing meter updates or creating orders. The same caveats apply to immediate order generation and CBM. Established limits should minimize extraneous order. Too many unwarranted orders can result in desensitization to requests generated from asset data.

Sending too many orders or not sending a necessary order can also create errors while requesting a new order. For example, a work order has been sent and is in process. If the condition comes in again, do we send another? Not all conditions will remain set until maintenance is complete and the system returned to service. Specific scenarios need to be worked out to ensure that a second order will not come through until the maintenance is complete.

Another condition could include how long a new order can be locked out after maintenance is complete. If the condition arises again, necessary maintenance could be missed. The technical implementation that adjusts the number of sent orders is straightforward (like resetting an alarm) but the business logic needs to be understood by all involved.

3.9 Why is PI the right bridge from OT to IT for CBM?

Many modern plants have deployed automated control and data collection systems to reduce operating errors, mistakes and time delays that can occur with manual data entry. Deploying a common software system between OT automation systems and business IT applications simplifies the integration and architecture of OT and IT systems. Maintaining this layer also offers the agility to rapidly take advantage of advances in IT applications and solutions without having to re-integrate or rip and replace your enterprise OT architecture.

The OT side of the house is concerned with safety, operational, environmental and other systems focused on production. These systems work with sensor-based data and control plant equipment in real time. This requires a significant focus on safety, security, compliance and effective operations. These systems tend to operate 7 days a week, 24 hours a day and usually involve redundancy to ensure no down time. The sensor-based data of OT systems is fundamentally different than the transactional nature of most IT systems.

The PI System is a time-series database. The majority of process and operating data generated and collected on critical infrastructure is time-series data from sensors. The PI System has myriad interfaces to collect data from source systems and can maintain data from many streams for long time periods. As the system of record for time series data, the PI System can be used as a single source or interface to non-time series systems such as CMMS. PI System Analytics can be used to convert high fidelity, streaming data into events, or conditions that should be infrequently sent to CMMS as transactions. This results in a single pathway from the OT networks, which tend to be more secure as they support critical infrastructure, to the IT network where CMMS and other enterprise applications exist and operate.

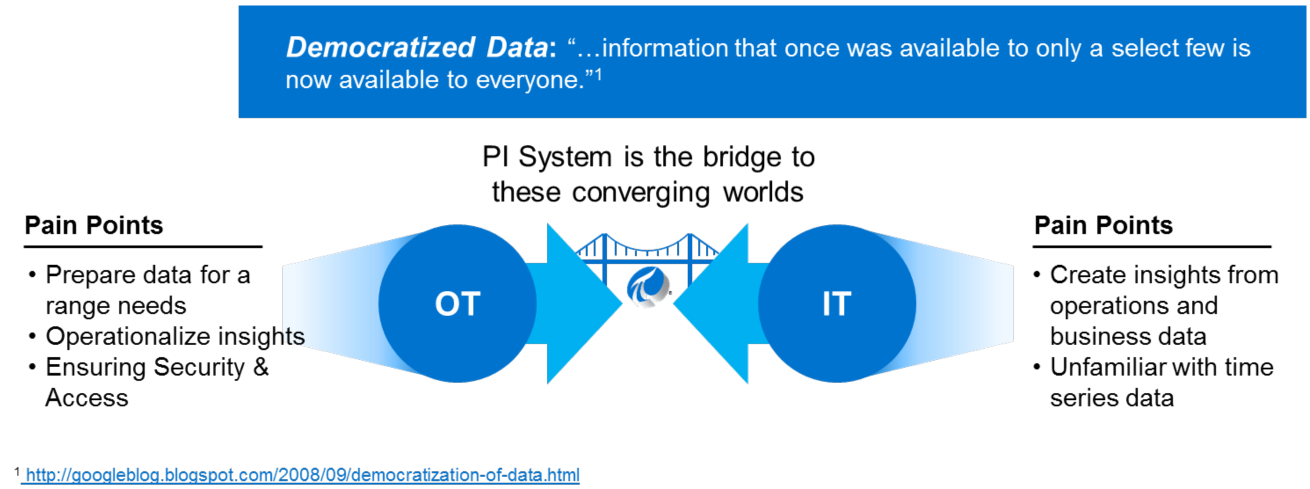


Figure 8 - The PI System as a Bridge from OT to IT

With this approach, time-series data is integrated with enterprise IT systems, bringing all critical asset data into one comprehensive framework where more advanced applications can be achieved. Automating the end-to-end process allows groups to refine their knowledge over time and continuously make systemic improvements across entire operations. Unified systems can scale across functional boundaries and provide a common operating platform and operational system of record. A system that meets these challenges should have these characteristics:

- support for open standards
- scalable
- highly secure
- highly available
- future-proof, evergreen architecture
- support for legacy automation and future data source systems
- positioned to leverage Big Data and business intelligence tools and techniques

4 An Introduction to the PI System

4.1 Overview

The PI System is an enterprise solution for collecting, storing, organizing, analyzing, and delivering time-series[3] information. The PI System collects large volumes of high-speed data at sub-second speeds. It organizes data by assets and events, and stores data for many years at the desired fidelity and rate. One of the goals of the PI System is to maintain full fidelity of a sensor's data over the lifetime of the sensor with a minimum of resources. The PI System delivers data to geographically dispersed users and systems. The PI System continues to collect, store, and make data available when servers are offline and during planned and unplanned network interruptions.

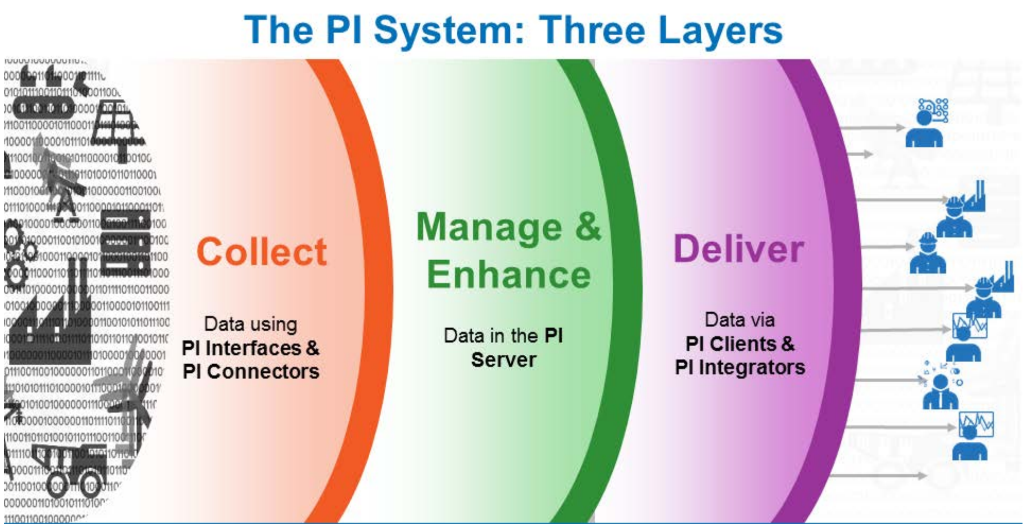


Figure 9 - The Three Layers of the PI System

There are several options for using PI System data. PI System Tools provide an easy and intuitive, graphical way to analyze and visualize data. PI Integrators create data sets to share with business intelligence tools from Microsoft, SAP, Esri, and others. Developer Technologies provide different methods for integrating PI System data with other software platforms or technologies and to create customized applications that run on top of the PI System.

The PI System uses multi-layered security to protect data so that only authorized users and systems can access data. Microsoft has certified the PI System to take advantage of the security features in recent Windows Server versions.

[3] Time series data is acquired continuously from sensors. This data is fundamentally different from transactional or "unstructured" data of IT systems, and is the domain of OT or Operations. Time series data generally comes from critical, control and monitoring systems, and more recently from Industrial Internet of Things (IIoT) architectures.

4.2 Collect Data

PI Interfaces and Connectors collect data from hundreds of source systems, and have been developed over several decades. OSIsoft has a reputation for providing the highest quality interfaces in the industry. The company has developed over 400 standard interfaces and connectors that collect data from the devices, control systems, and supervisory systems of all major vendors.

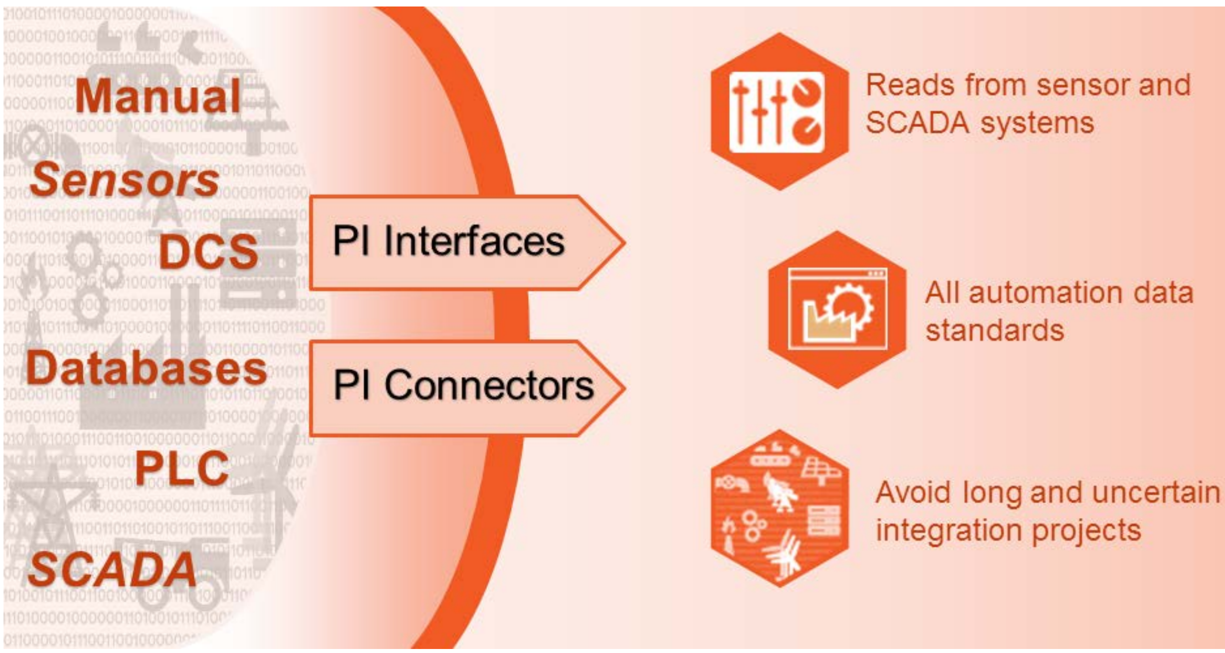


Figure 10 - PI Interfaces and Connectors

PI Interfaces create high-speed links to data sources to supply real-time data to the PI Data Archive. The interfaces collect data from distributed control systems, programmable logic controllers, SCADA and HVAC systems, sensors, and other sources and deliver the data to the PI Data Archive. PI Interfaces connect to the products of all major automation vendors including Schneider, General Electric, Siemens, Honeywell, Emerson, Rockwell, Yokogawa, and ABB. The interfaces support popular standards including OPC, Modbus, OLEDB, SNMP, BACnet, C37.118, TCP/IP, and RDBMS.

PI Connectors are OSIsoft's newest data collection technology. They require less configuration than PI Interfaces. PI Connectors improve on the performance and scalability of the data collection capabilities of the PI System, and are easy to deploy and manage. They simplify data collection by automatically scanning devices for specific protocols. The connectors create PI Points to store data and automatically create models for assets.

4.3 Manage and Enhance Data

The PI Server consolidates data collected by PI Interfaces and PI Connectors into a single system. It secures the data and delivers it only to authorized users. The PI Server uses the least amount of system resources possible to store data while maintaining original sensor fidelity. A user can retrieve data —no matter how old — quickly, accurately, and securely. Customers keep decades of data online in the PI Server.

	Data Archive — Store large volumes of data for decades and rapidly deliver data to thousands of client applications.
	Asset Framework — Store metadata in a Microsoft SQL database about all data sources that are in the PI Server.
	Event Frames — Define batch processes, anomalies, fixed periods and other repeatable events—such as days, shifts, startups, and downtime—that have a start and end time.
	Notifications — Build and send real-time alerts to people and systems.
	PI Server Tools and Utilities — Administer the PI System with easy-to-use, graphical Windows-based applications.

Figure 11 - PI System Components

Data Archive stores time-stamped data. It can store data for up to 20 million tags and capture hundreds of thousands of events per second. It can provide millions of time-stamped events per second to thousands of concurrent client application connections. Typical queries from users take just a few seconds to retrieve millions of time-stamped events from the Data Archive.

Asset Framework stores metadata in a Microsoft SQL database. With Asset Framework, users can define models for equipment and other assets and use these models to create simple and complex analyses. An asset model can be configured to organize and structure PI System data and other data according to objects that users are most familiar with, such as physical objects in production processes (e.g. CMMS). It is easy to define and build models that reflect the process flow between assets.

Event Frames defines batch processes and other repeatable events (such as days, shifts, startups, and downtime) that have a start and end time. For each event type a user can create an index for the attributes that are used most often. Data from specific events can be compared, analyzed, and included in reports.

Notifications delivers messages in real time that alert people and systems when key events occur. Users can customize and control all aspects of their notifications.

PI Server Tools and Utilities is a set of applications for managing data archives, configuring security settings, creating new tags, accessing message logs, configuring interfaces, and handling many other PI System administrative tasks.

4.4 Deliver Data

The PI System has many options for analyzing and visualizing data, and for integrating data with business intelligence, geospatial, big data, and other third-party tools and systems.

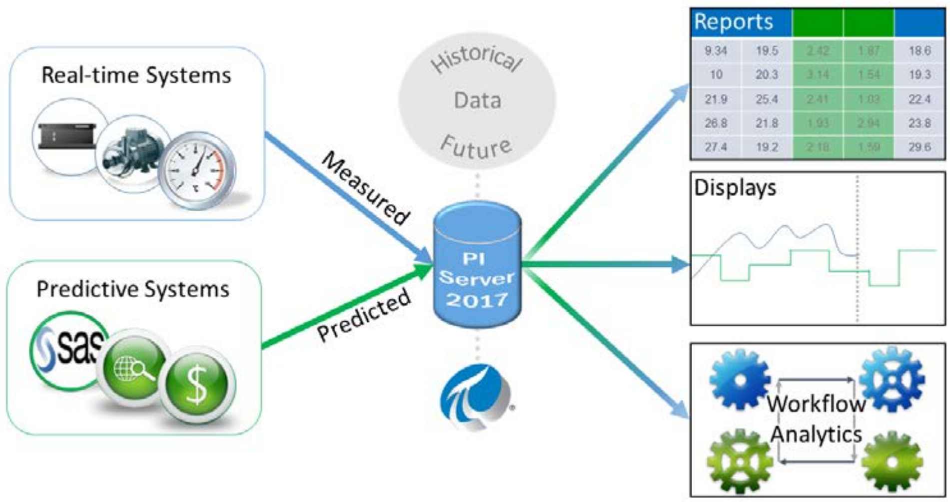


Figure 12 - Data Flow with the PI System

4.4.1 Analyze Data

PI Asset Analytics is a suite of computational and analytical tools. The PI System's calculation capabilities support everything from simple averages, minimums, and standard deviations to complex predictive equipment models, what-if analyses, and multifaceted logic.

PI Analysis Service — Configure, schedule, and run calculations on PI Asset Framework attributes.

Performance Equations — Implement sophisticated real-time calculations using PI System data. Calculations can include unit performance, real-time yield and cost accounting, batch summary, conversions and logical operations.

Totalizers — Perform common calculations such as totals, averages, minimum and maximum values, and standard deviations. Totalizers are practical for totaling measurements or other process variables such as end of day yields at the end of specific periods.

PI Real-Time SQC — Use numerical methods to monitor the characteristics of a process and make sure they remain within pre-determined boundaries. When an unacceptable deviation occurs in a process, SQC Alarms alert the appropriate people.

4.4.2 Visualize Data

PI System visualization tools are used for viewing data on desktops and mobile devices. Users can configure displays and spreadsheets, use built-in calculations, and create new calculations. They can create and distribute reports and share data offline or over the web without writing code. The tools provide the information that users need to monitor processes in real time, analyze historical performance, and compare current conditions with past results and future predictions. PI System visualization tools integrate with Microsoft Office, so PI System users can easily collaborate with non-PI System users.

	PI Vision — Perform ad hoc analysis on PI System data and share insights with others using this intuitive, web-based tool.
	PI ProcessBook — Build dynamic, interactive, process displays to help users view and analyze data.
	PI DataLink — Create reports and perform detailed calculations using the familiar spreadsheet environment of Microsoft Excel.
	PI Manual Logger — Manually collect data and send it to the PI Server.
	PI WebParts — Access PI System data through a library of auto-updating SharePoint web parts.

Figure 13 - PI System Visualization

PI Vision is a web-based tool that gives users access to PI System data on a variety of devices. PI Vision includes integrated searching, intuitive controls, a modern user interface, and powerful visualization tools. Users can perform ad hoc analysis, quickly discover answers, and share read-only versions of displays.

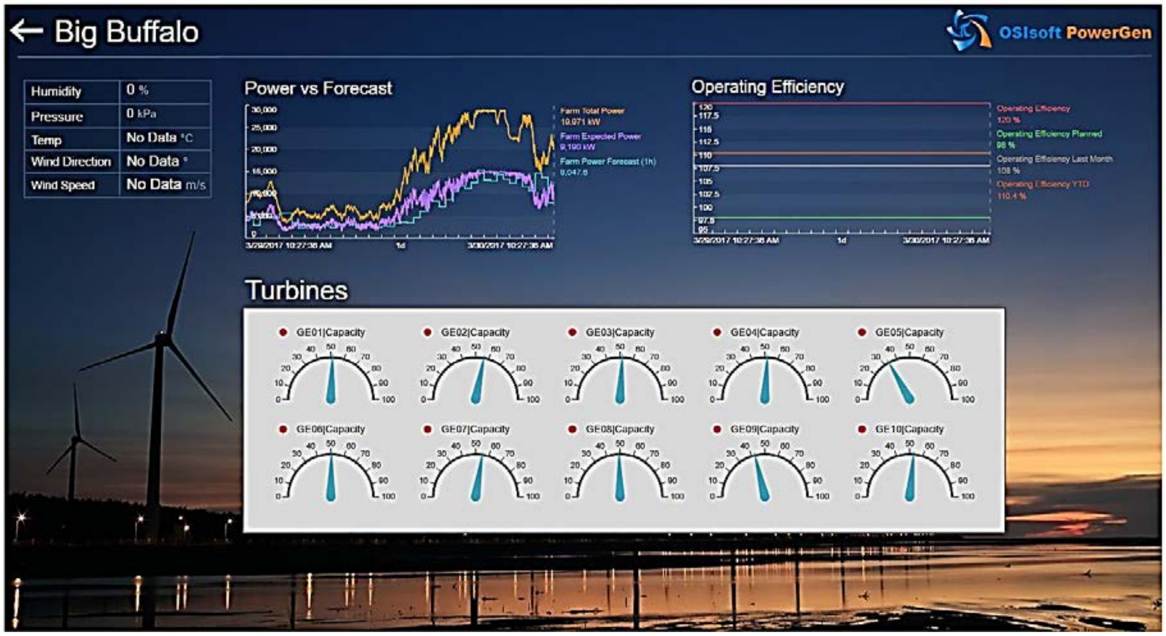


Figure 14 - PI Vision displays data in trends, tables, values, and gauges on a variety of devices.

PI ProcessBook has a Microsoft-style graphical user interface and extensive design tools for creating, modifying, and enhancing displays. PI ProcessBook includes a symbol library with over 3,000 images with many configuration options. Symbols and the lines connecting them move in tandem. Multistate symbols can change color, flash, or disappear. PI ProcessBook displays can include layers, so elements in a display can be viewed or made invisible as layers are toggled on and off. Users can share read-only versions of their displays.

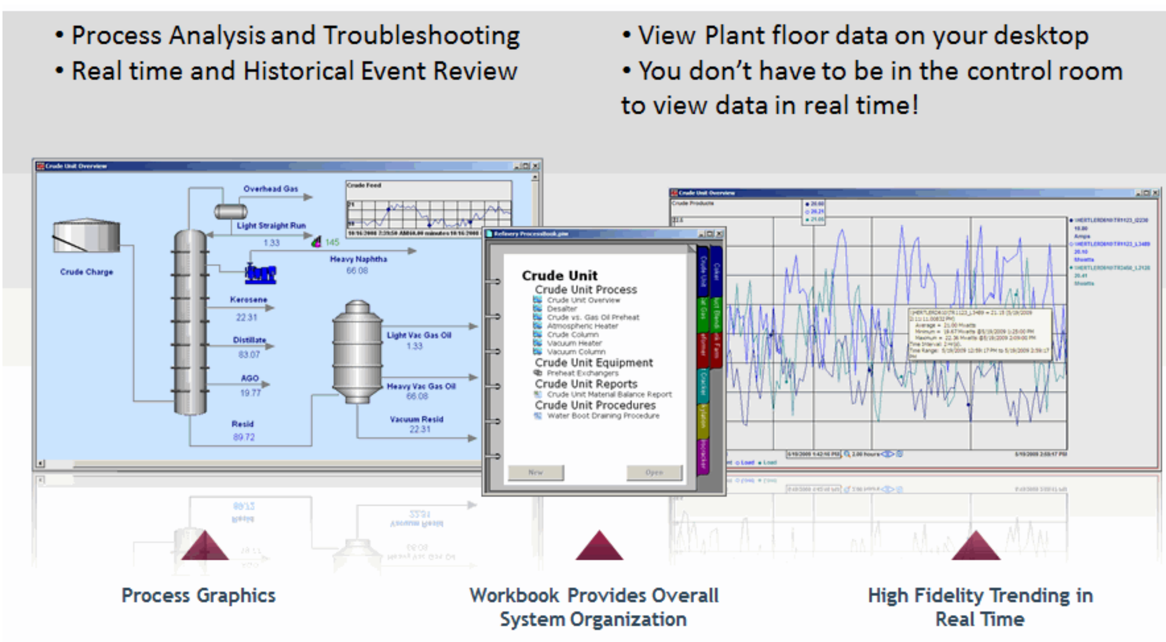


Figure 15 - PI ProcessBook displays feature a wide range of configuration options for comparing historical, real-time, and future data about assets.

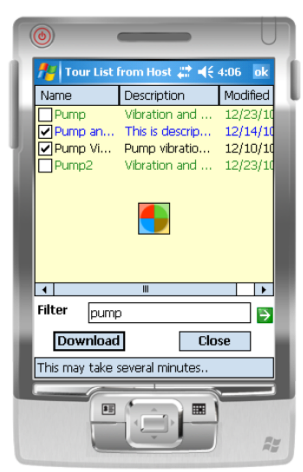
PI DataLink is an add-in to Microsoft Excel that creates a bi-directional connection between the PI System and Excel. Users can apply the familiar and powerful analytic capabilities of Excel to all their PI System data. PI DataLink makes data gathering, reporting, modeling, analysis, forecasting, and process planning fast and easy. Data in PI DataLink spreadsheets can be configured to refresh manually or automatically on a schedule. Users can create spreadsheets and use them as templates for frequently-generated reports.

COLUMN WEEKLY REPORT

Unit	Column	2013-05-01 Thursday	2013-05-02 Friday	2013-05-03 Saturday	2013-05-04 Sunday	2013-05-05 Monday	2013-05-06 Tuesday	2013-05-07 Wednesday	Deviation from target [mHUF/week]
Distillation	DARED 101								-1,11623
	DCDU3 105	N/A	N/A	N/A					0,02135
	DGFRU 112								0,86768
	DGFRU 118	N/A							0,00938
	DGFRU 123								0,71449
Aromatics	DAEDB 1/101								-0,31899
	DAEDB 2/108								0,30235
	DAEDB K1								0,15184
Motorfuel	DFCC 840V2								-0,75675
	DETBE 450V2								0,46290
	DETBE 450V3								0,01197
	DETBE 450V4								0,33566
	DMHCK K803								1,14934
	DGHT3 K501								-0,03649
	DGHT3 K803								-0,34319
	DSRU6 T501								-0,38648
	DSRU6 T801								0,45209
Residue	DDCKU T106								0,58097
	DDCKU T109								-0,56480
	DDCKU T201								0,28825
Tisza Refinery	TGOK C10								-0,30423
	TMTB C104	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
								Total -:	*-1,67239*
								Total +:	3,18412
								SubTotal:	**1,52111**

Figure 16 - This DataLink report summarizes data from the PI System on energy use. The right column shows the amount of money in local currency that each unit in the refinery was either over or under budget for the week. The green, yellow, and red circular icons give a quick overview of the daily budgetary performance at each unit.

PI Manual Logger enables manual collection of data to send to the PI Server. Users can collect data from operator rounds, lab results, plant surveillance, and field inspections and enter the data on a PC or mobile device. They can import data from an XML file into PI Manual Logger and review, edit, and validate the data before sending it to the PI Server. PI Manual Logger and PI Manual Logger Mobile support data entry offline and while disconnected from the PI Server. Data can be uploaded to the PI Server wirelessly and through wired connections. Manually entered tag values and comments can be reviewed and analyzed. Data can be submitted, reviewed, and edited before it is uploaded to the PI Server. Users can enter values and comments for each tag. Text entries can be made by using voice-text capabilities on supported devices.



PI WebParts provides intranet and Internet access to PI System data through a library of auto-updating SharePoint web parts. Data from any source, including real-time PI Systems and non-PI Systems, can be displayed anywhere in easy-to-understand visualizations such as graphs, dials, and key performance indicators.

4.4.3 Integrate Data

Many companies have a desire to integrate PI System data (time series information) with other IT systems, reporting platforms and big data analytics. OSIsoft developed several methods for sharing PI System data that use standard technologies. Advanced Integrations export PI System data to external systems. Developer Technologies are used to build applications that interoperate with the PI System.

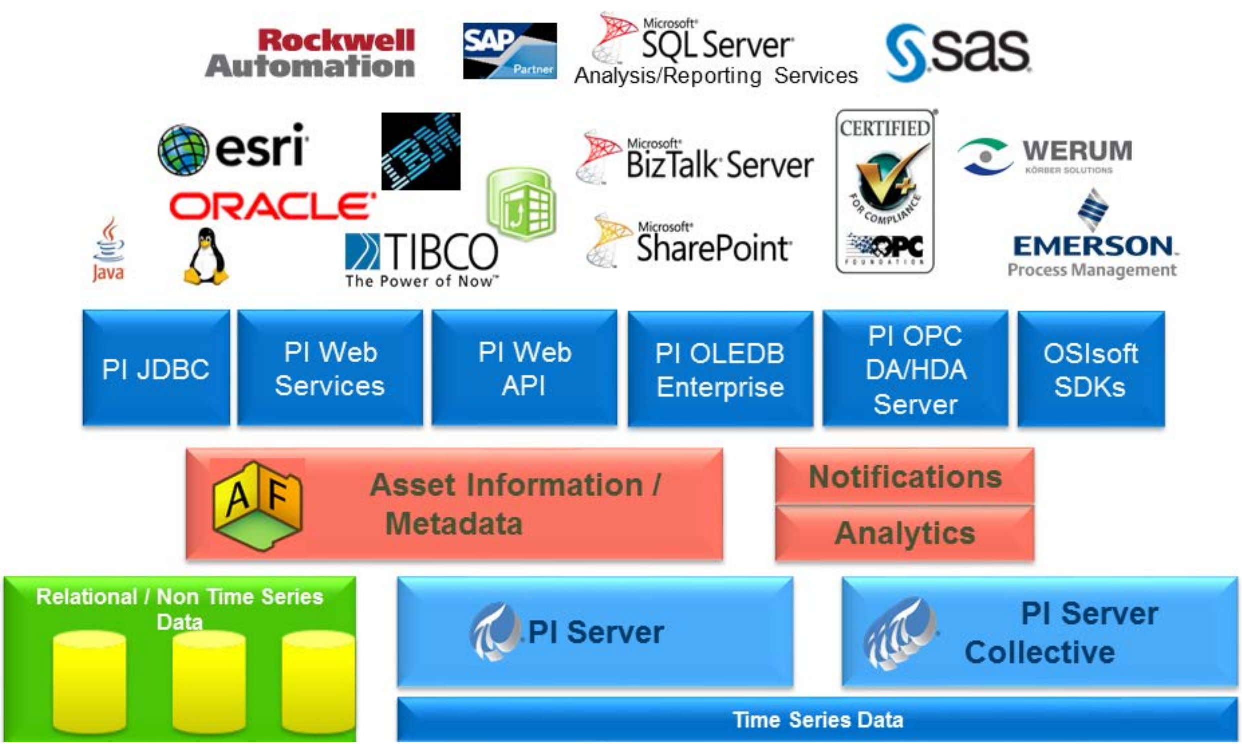


Figure 17 - The PI System stack for integration

esri	PI Integrator for Esri® ArcGIS® — Combine time-series data from the Data Archive with the Esri ArcGIS platform.
	PI Integrator for Azure — Present PI System data so that it can be used by Cortana and Power BI for reporting, visualization, and analysis.
Powered by SAP HANA®	PI Integrator for SAP HANA — Use data from the PI System with SAP HANA.
Microsoft Business Intelligence	PI Integrator for Business Analytics — Make PI System data accessible to business intelligence tools such as Tableau, Tibco Spotfire, Hadoop, and Microsoft BI.
PI WEB API	Developer Technologies — Develop custom applications to integrate PI System data into third-party applications and business systems.

Figure 18 - PI System Integrators and Developer Technologies

PI Integrator for Esri ArcGIS exports data from the PI System to the Esri ArcGIS platform. The integrator delivers time-series data from the PI Data Archive so it can be displayed with geographic context in maps. PI Integrator for Esri ArcGIS provides:

- A configuration portal to identify assets that are being displayed on maps.
- A component for quick and easy integration with PI Vision.
- A component for creating AF Templates and Elements that have been read from a map.

PI Integrator for Esri ArcGIS works with Esri Portal for ArcGIS Server Extension and ArcGIS Online.

Figure 19 - Time series data from the PI Data Archive is displayed with geographic context provided by the Esri ArcGIS platform.

PI Integrator for Microsoft Azure presents PI System data, context and events so they can be used in Cortana and Power BI for reporting, visualization, and analysis. The integrator presents time-series data and event and asset context that have been cleansed, augmented, and shaped, to provide PI System data to Azure. It enables the enterprise to use business intelligence tools like Power BI and integrate data with SQL Data Warehouse or Azure SQL. The integrator provides easy access to analysis-ready data for machine learning via Azure ML (part of Cortana Intelligence Suite).

PI Integrator for SAP HANA presents data from the PI System for use with SAP HANA via SAP Smart Data Access. PI System data can be used for reporting, analytics, and application integrations. PI Integrator for SAP HANA utilizes the Data Provisioning Agent included with the Enterprise Information Management capability of SAP HANA to enable high performance and secure integration with data systems like the PI Server.

PI Integrator for Business Analytics makes PI System data accessible to business intelligence tools for reporting and analytics. The Integrator delivers data to Tableau, Tibco Spotfire, and Microsoft BI (Excel, PowerPivot, PowerView, and PowerQuery). It works with any software that can use an ODBC data source connection. The Integrator exposes time-series data with context about assets and related events. Data are modeled, cleansed, and structured to allow business intelligence tools to browse, query, and consume PI System data.

Developer Technologies provide tools for developing custom applications and integrating PI System data into other applications and business systems. Developer Technologies include: SQL-based tools for accessing the PI System like a relational database; PI Web API; PI .NET framework; PI OPC DA Server, and PI OPC HDA Server. The technologies make PI System data available to use with other applications and business systems such as Microsoft Office or SQL Server, enterprise resource planning systems, manufacturing execution systems, business intelligence and big data analysis tools, laboratory information management systems, reporting and analytics platforms, web portals, geospatial software, and maintenance systems among others.

4.5 PI System for Condition Monitoring and CBM

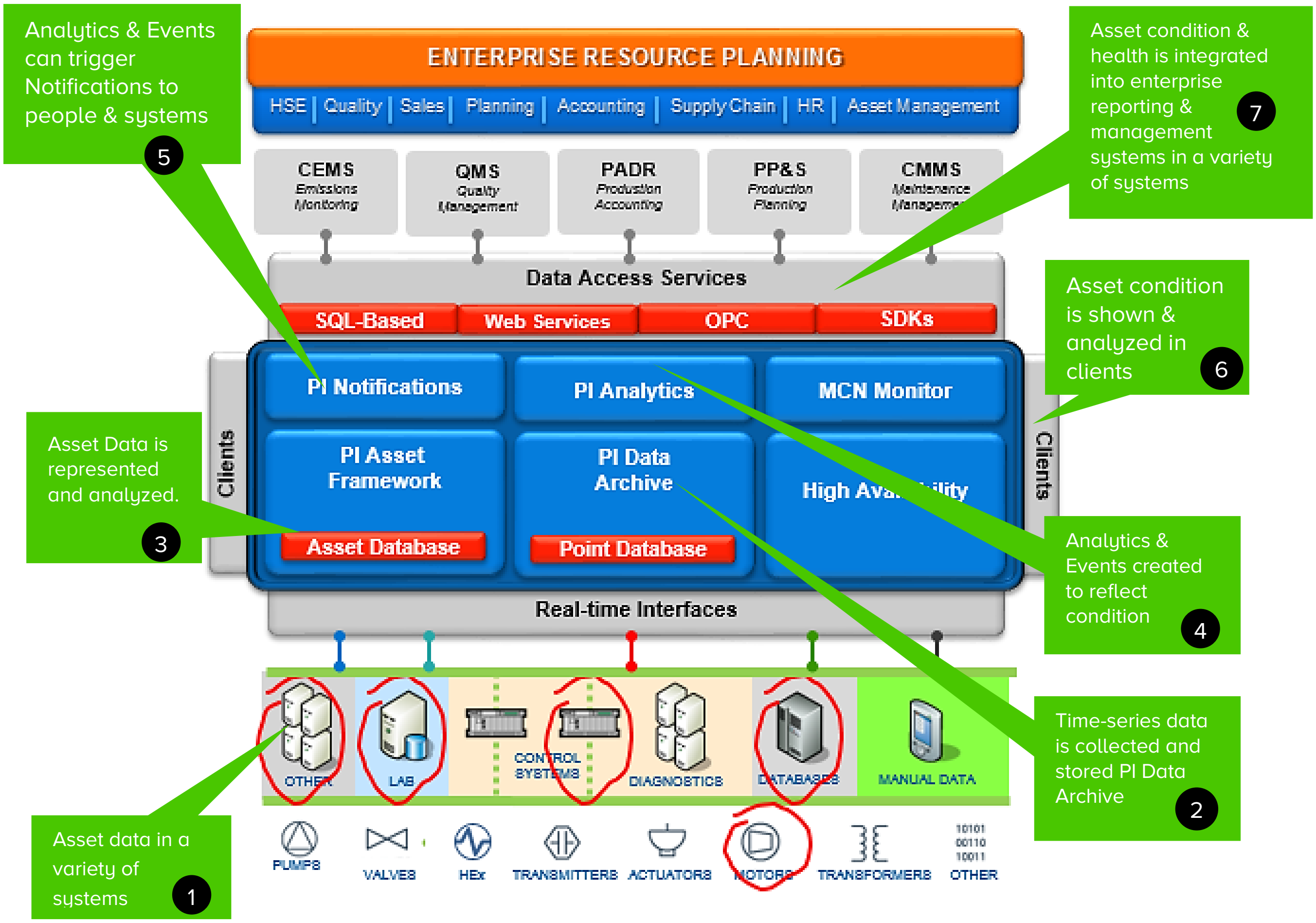


Figure 20 - PI System: an Ecosystem for Condition Monitoring

Figure 20 shows the PI System integrated with data sources and enterprise systems for condition monitoring and condition-based maintenance (CBM). The steps pictured above and enumerated by the black dots show a sequential flow through the ecosystem:

1. Asset data have disparate sources and exist in a variety of systems. Data are often managed/evaluated to determine parameters that most effectively drive maintenance health/condition and/or are used to determine maintenance activities (for example, run time, and operations/cycles). See Figure 21 below.

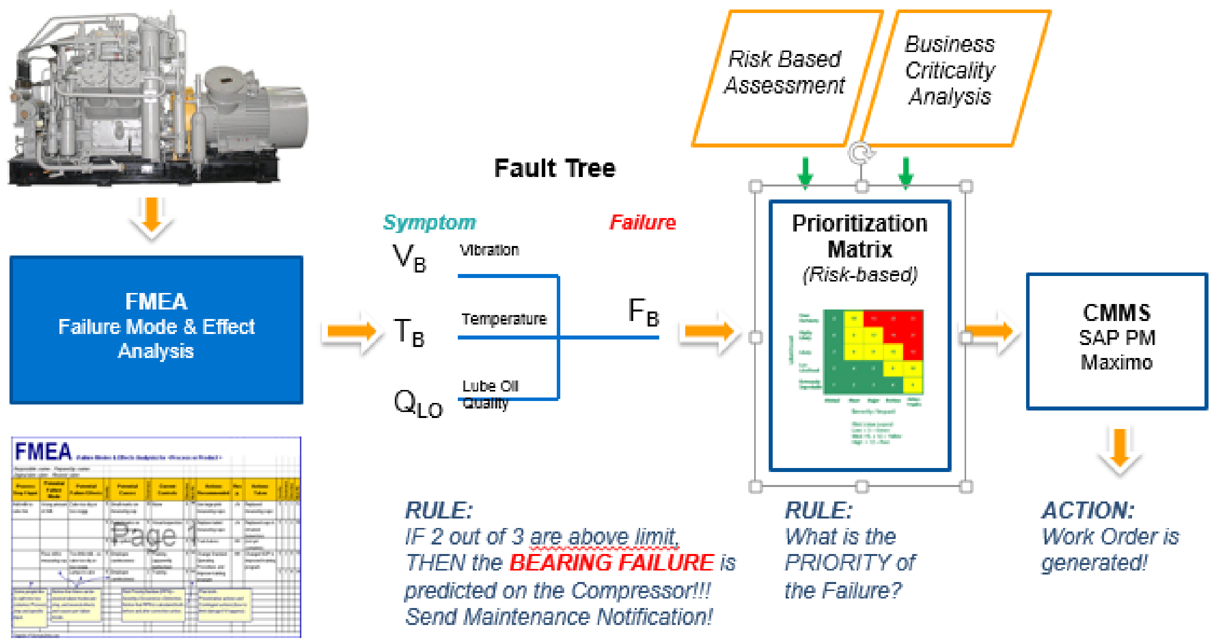


Figure 21 – Developing a Strategy for Condition Monitoring

2. Data are acquired through PI interface nodes and stored in the PI Data Archive for simple retrieval and analysis. Data streams are called “tags.”

```
TIME STAMP.......05/09/2008;15:12:03
TAG NAME.........TI201A.PV
VALUE............75
UOM..............DegC
ANNOTATION.......C201 Bearing Temp.
```

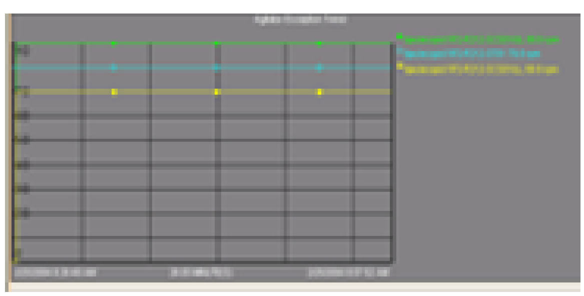


Figure 22 - Visualization example of condition parameter

3. Assets are represented as elements within PI Asset Framework (AF) and are organized for easy access in support of analytics (for example, by providing rollups). This representation can include static data, access to streaming data, calculations to assist in condition determination, data from external systems (for example, nameplate and CM/PM ratio).

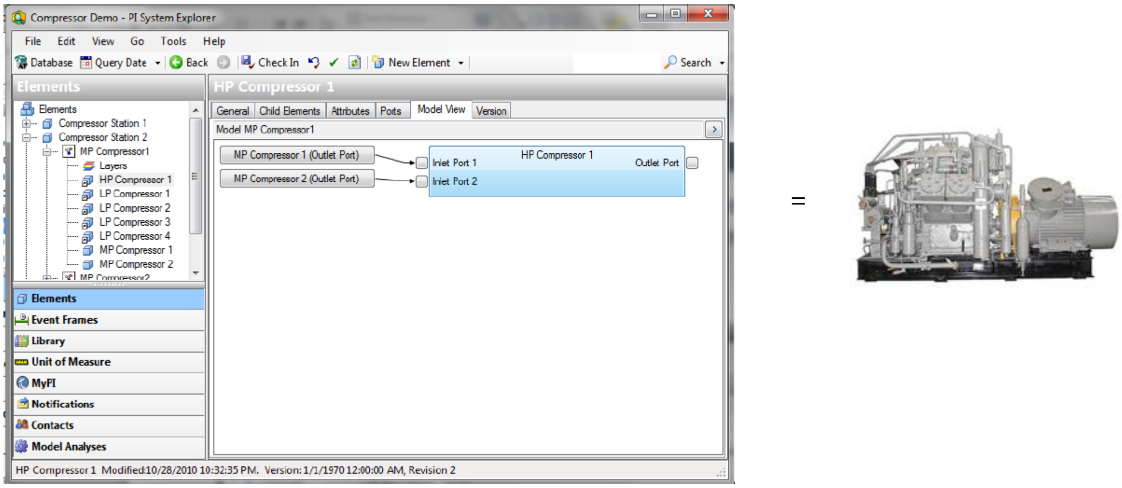


Figure 23 - Example asset definition in PI Asset Framework (AF)

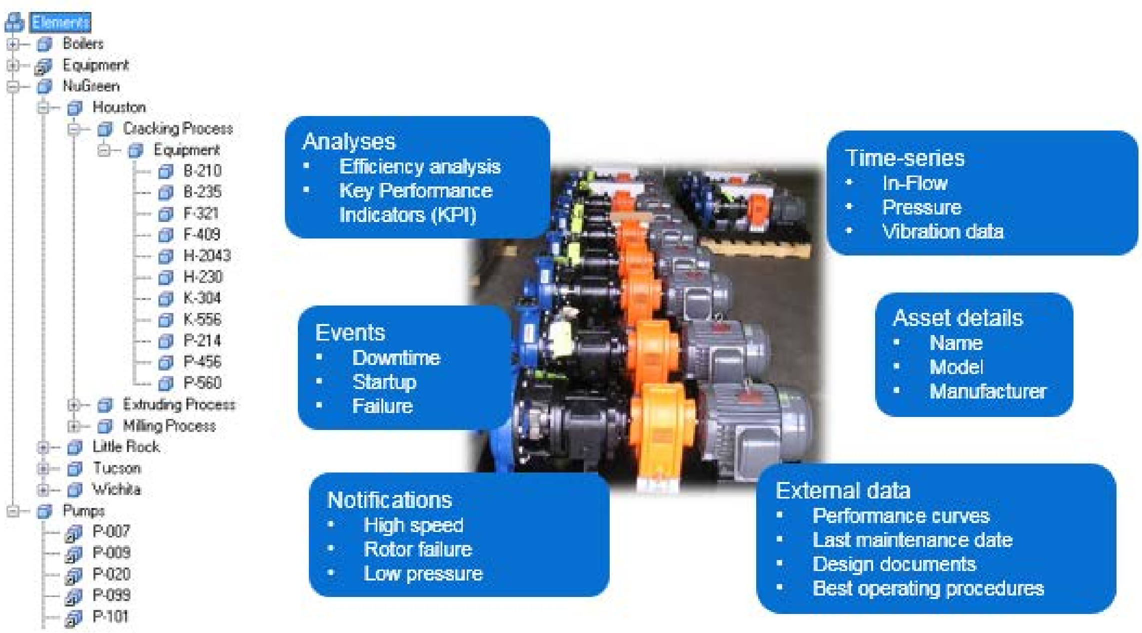


Figure 24 - AF Elements as assets example hierarchy and types of data typically in AF

In many cases, multiple sources provide data to populate AF (as shown in Figure 24). CMMS plant locations and physical equipment descriptions are good starting points for static data such as nameplates and object information needed to send data from the PI System to CMMS.

The tag list is needed to map tags to asset attributes. Remember that CBM is a process. Get started by mapping critical equipment and critical attributes. Once assets, attributes and their data streams are mapped in AF, payback is achieved every time somebody accesses data for CBM as well as other activities supporting operational intelligence.

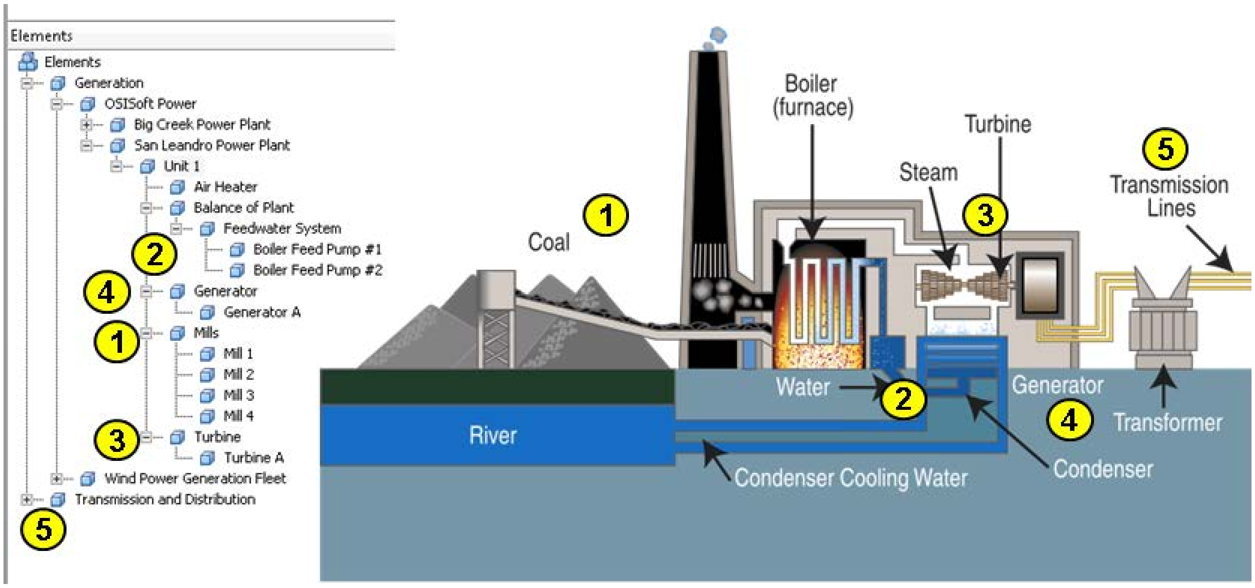


Figure 25 - Modeling a Power Plant in an AF Structure.

4. Analytics and events often capture asset conditions. These can be very simple or very complex calculations and business rules. For example, they can identify periods of high vibration, and low pump efficiency, or calculate an aggregation of run time and material processed. We can also combine individual condition factors into a health score for the asset.

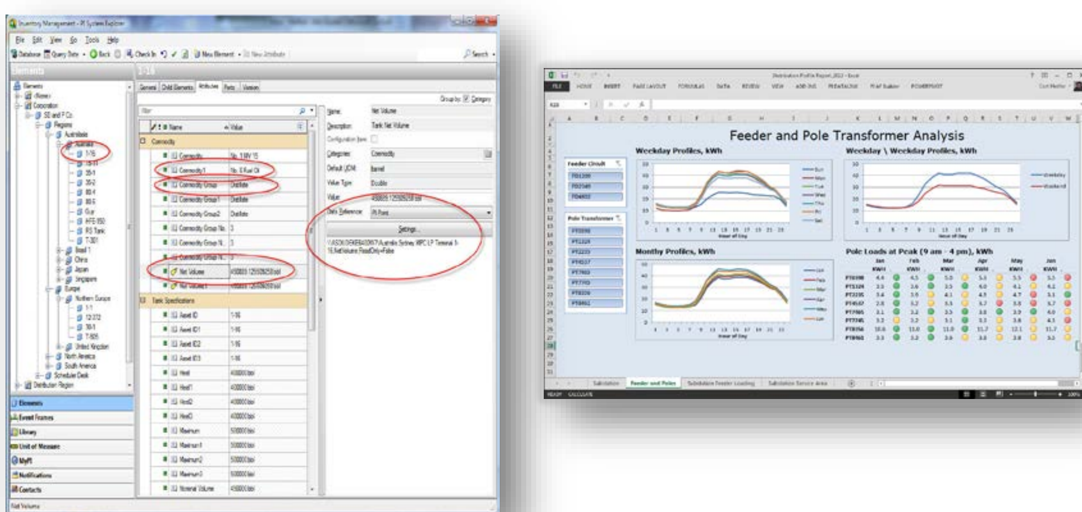


Figure 26 – Example Calculations and Analyses using PI AF

5. Analysis results and events can send notifications to alert an individual of a condition or update another enterprise system. For example, PI Notifications can send an email to an engineer to indicate that a specific condition has occurred, or update CMMS with a meter (operation) count.

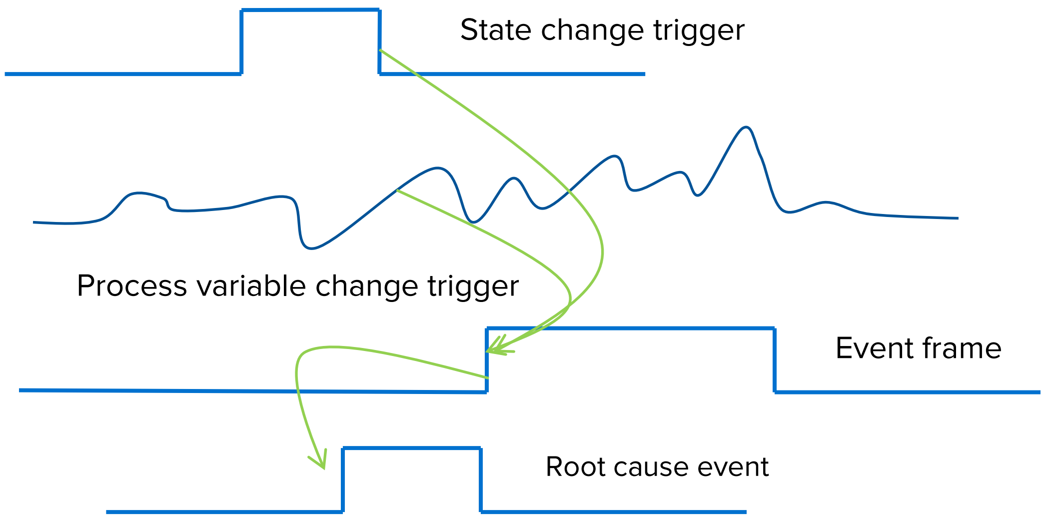


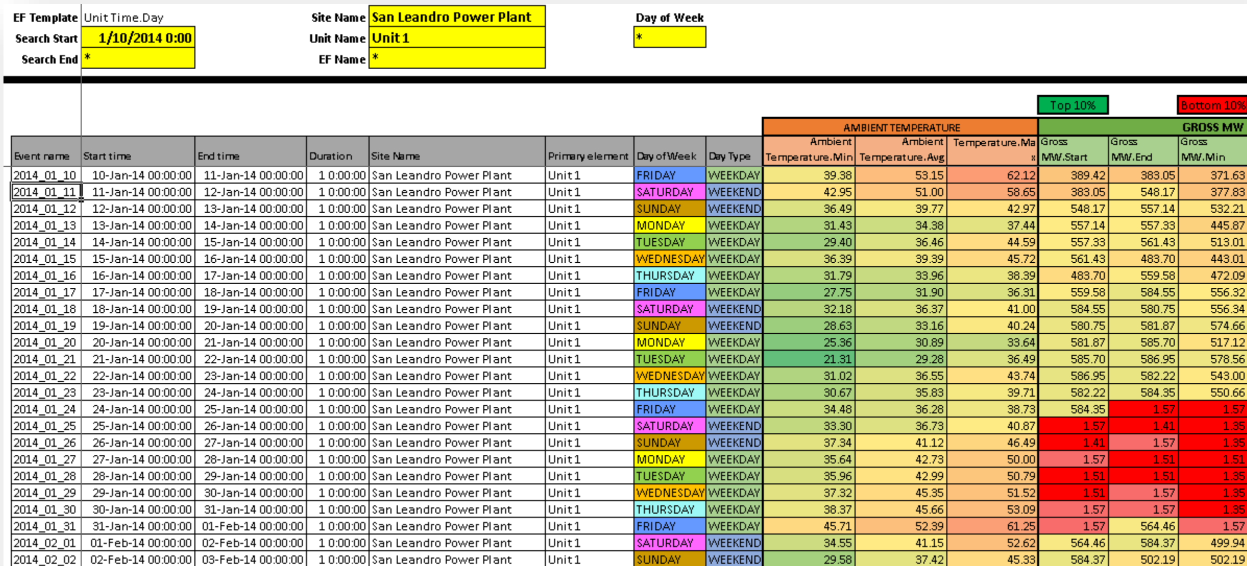
Figure 27 - Example flows of event frame creation

A PI event frame is a repeatable event with a defined start and end time. CBM events can be layered to gain insight about how the assets have operated over periods of time by comparing them to each other over these time segments. In Figure 27 an event frame is initiated by a trigger that could be a state change in process data. Process variable exceptions such as a rate of change exceeding a limit, or operation count over a specified number of times within a time period can also initiate an event frame.

Asset analytics can use sophisticated calculations to define reference events based on process data.   A root cause event frame can capture or reference data before the actual trigger of an event frame. For example, when a unit or piece of equipment trips we may want to see specific data for a time period before this event to determine the root cause event or conditions.

Events capture the frames (or bookmarks) that define the event, the configurable time period before the event trigger, the referenced element or asset, specific attribute data, and other calculations such as duration and cost. Event frames capture data as referenced and defined within the event frame template. They also provide placeholders for additional data to be added later. For example, they can include cause code values when an engineer determines the cause of the event, or programmatic data returned from an integration with the CMMS such as the Work Order (WO) number.

6. You can make this information accessible in PI client applications and other enterprise systems through PI Data Access technologies. Event and other analytical data surfaced for consumption by knowledge workers and analysts allows them to interpret specific asset conditions and evaluate them over time. Root cause analysis proceeds quickly when you can identify trends relative to asset nameplate and process data.



EF Template	Unit Time.Day	Site Name	San Leandro Power Plant	Day of Week	*
Search Start	1/10/2014 0:00	Unit Name	Unit 1		
Search End	*	EF Name	*		

Top 10% | Bottom 10%

								AMBIENT TEMPERATURE			GROSS MW		
Event name	Start time	End time	Duration	Site Name	Primary element	Day of Week	Day Type	Ambient Temperature.Min	Ambient Temperature.Avg	Temperature.Max	Gross MW.Start	Gross MW.End	Gross MW.Min
2014_01_10	10-Jan-14 00:00:00	11-Jan-14 00:00:00	1 0:00:00	San Leandro Power Plant	Unit 1	FRIDAY	WEEKDAY	39.38	53.15	62.12	389.42	383.05	371.63
2014_01_11	11-Jan-14 00:00:00	12-Jan-14 00:00:00	1 0:00:00	San Leandro Power Plant	Unit 1	SATURDAY	WEEKEND	42.95	51.00	58.65	383.05	548.17	377.83
2014_01_12	12-Jan-14 00:00:00	13-Jan-14 00:00:00	1 0:00:00	San Leandro Power Plant	Unit 1	SUNDAY	WEEKEND	36.49	39.77	42.97	548.17	557.14	532.21
2014_01_13	13-Jan-14 00:00:00	14-Jan-14 00:00:00	1 0:00:00	San Leandro Power Plant	Unit 1	MONDAY	WEEKDAY	31.43	34.38	37.44	557.14	557.33	445.87
2014_01_14	14-Jan-14 00:00:00	15-Jan-14 00:00:00	1 0:00:00	San Leandro Power Plant	Unit 1	TUESDAY	WEEKDAY	29.40	36.46	44.59	557.33	561.43	513.01
2014_01_15	15-Jan-14 00:00:00	16-Jan-14 00:00:00	1 0:00:00	San Leandro Power Plant	Unit 1	WEDNESDAY	WEEKDAY	36.39	39.39	45.72	561.43	483.70	443.01
2014_01_16	16-Jan-14 00:00:00	17-Jan-14 00:00:00	1 0:00:00	San Leandro Power Plant	Unit 1	THURSDAY	WEEKDAY	31.79	33.96	38.39	483.70	559.58	472.09
2014_01_17	17-Jan-14 00:00:00	18-Jan-14 00:00:00	1 0:00:00	San Leandro Power Plant	Unit 1	FRIDAY	WEEKDAY	27.75	31.90	36.31	559.58	584.55	556.32
2014_01_18	18-Jan-14 00:00:00	19-Jan-14 00:00:00	1 0:00:00	San Leandro Power Plant	Unit 1	SATURDAY	WEEKEND	32.18	36.37	41.00	584.55	580.75	556.34
2014_01_19	19-Jan-14 00:00:00	20-Jan-14 00:00:00	1 0:00:00	San Leandro Power Plant	Unit 1	SUNDAY	WEEKEND	28.63	33.16	40.24	580.75	581.87	574.66
2014_01_20	20-Jan-14 00:00:00	21-Jan-14 00:00:00	1 0:00:00	San Leandro Power Plant	Unit 1	MONDAY	WEEKDAY	25.36	30.89	33.64	581.87	585.70	517.12
2014_01_21	21-Jan-14 00:00:00	22-Jan-14 00:00:00	1 0:00:00	San Leandro Power Plant	Unit 1	TUESDAY	WEEKDAY	21.31	29.28	36.49	585.70	586.95	578.56
2014_01_22	22-Jan-14 00:00:00	23-Jan-14 00:00:00	1 0:00:00	San Leandro Power Plant	Unit 1	WEDNESDAY	WEEKDAY	31.02	36.55	43.74	586.95	582.22	543.00
2014_01_23	23-Jan-14 00:00:00	24-Jan-14 00:00:00	1 0:00:00	San Leandro Power Plant	Unit 1	THURSDAY	WEEKDAY	30.67	35.83	39.71	582.22	584.35	550.66
2014_01_24	24-Jan-14 00:00:00	25-Jan-14 00:00:00	1 0:00:00	San Leandro Power Plant	Unit 1	FRIDAY	WEEKDAY	34.48	36.28	38.73	584.35	1.57	1.57
2014_01_25	25-Jan-14 00:00:00	26-Jan-14 00:00:00	1 0:00:00	San Leandro Power Plant	Unit 1	SATURDAY	WEEKEND	33.30	36.73	40.87	1.57	1.41	1.35
2014_01_26	26-Jan-14 00:00:00	27-Jan-14 00:00:00	1 0:00:00	San Leandro Power Plant	Unit 1	SUNDAY	WEEKEND	37.34	41.12	46.49	1.41	1.57	1.35
2014_01_27	27-Jan-14 00:00:00	28-Jan-14 00:00:00	1 0:00:00	San Leandro Power Plant	Unit 1	MONDAY	WEEKDAY	35.64	42.73	50.00	1.57	1.51	1.51
2014_01_28	28-Jan-14 00:00:00	29-Jan-14 00:00:00	1 0:00:00	San Leandro Power Plant	Unit 1	TUESDAY	WEEKDAY	35.96	42.99	50.79	1.51	1.51	1.35
2014_01_29	29-Jan-14 00:00:00	30-Jan-14 00:00:00	1 0:00:00	San Leandro Power Plant	Unit 1	WEDNESDAY	WEEKDAY	37.32	45.35	51.52	1.51	1.57	1.35
2014_01_30	30-Jan-14 00:00:00	31-Jan-14 00:00:00	1 0:00:00	San Leandro Power Plant	Unit 1	THURSDAY	WEEKDAY	38.37	45.66	53.09	1.57	1.57	1.35
2014_01_31	31-Jan-14 00:00:00	01-Feb-14 00:00:00	1 0:00:00	San Leandro Power Plant	Unit 1	FRIDAY	WEEKDAY	45.71	52.39	61.25	1.57	564.46	1.57
2014_02_01	01-Feb-14 00:00:00	02-Feb-14 00:00:00	1 0:00:00	San Leandro Power Plant	Unit 1	SATURDAY	WEEKEND	34.55	41.15	52.62	564.46	584.37	499.94
2014_02_02	02-Feb-14 00:00:00	03-Feb-14 00:00:00	1 0:00:00	San Leandro Power Plant	Unit 1	SUNDAY	WEEKEND	29.58	37.42	45.33	584.37	502.19	502.19

Figure 28 - Example Production Summary Report by Unit

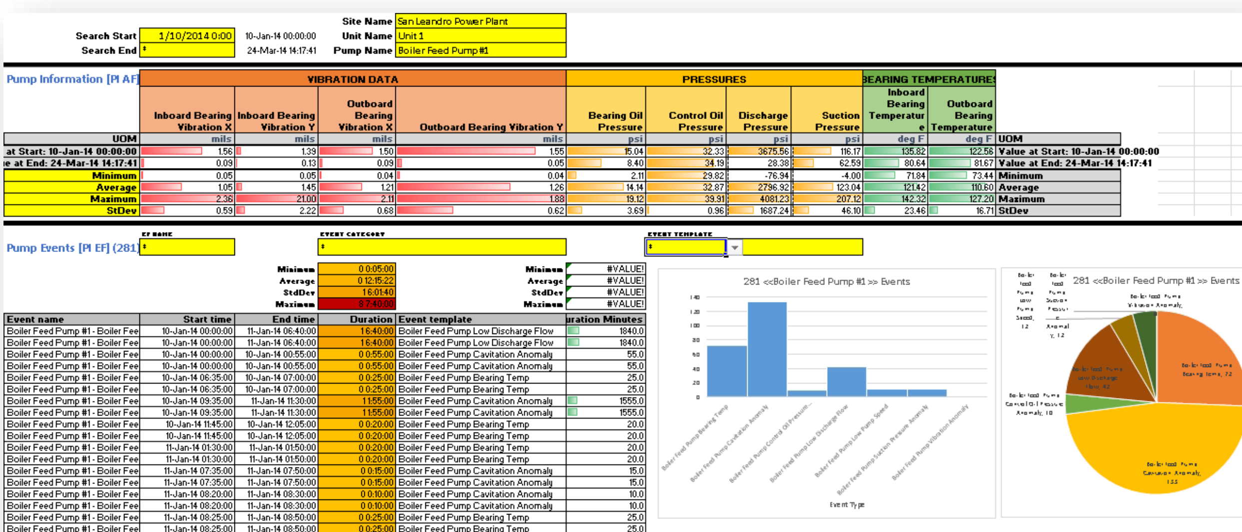


Figure 29 - Example Event Frame Analytics of Vibration Data on Feedwater Pumps

The two sample reports above are just quick examples of complex reports easily created using Microsoft Excel and acquiring event data from the PI System using PI DataLink. These reports are numerical analysis reports useful for evaluating events for a specific asset and events across many assets and asset types. They also represent asset performance monitoring plans and are used to review performance of an asset over a period.

7. Finally, you can integrate asset data into CMMS and other enterprise applications in a number of ways. Section 5 contains more specifics on the integration of PI System with a CMMS. There are two basic scenarios: push or pull.

   Push sends data to people and systems using delivery channels such as sending emails or invoking a web service. PI System Access technologies enable the pull model, where enterprise applications can acquire data from the PI System using technologies including popular open standards methods such as ODBC and REST-based web services.

5 PI System integration with CMMS

This section provides an overview of methods used to integrate PI System data with CMMS applications.

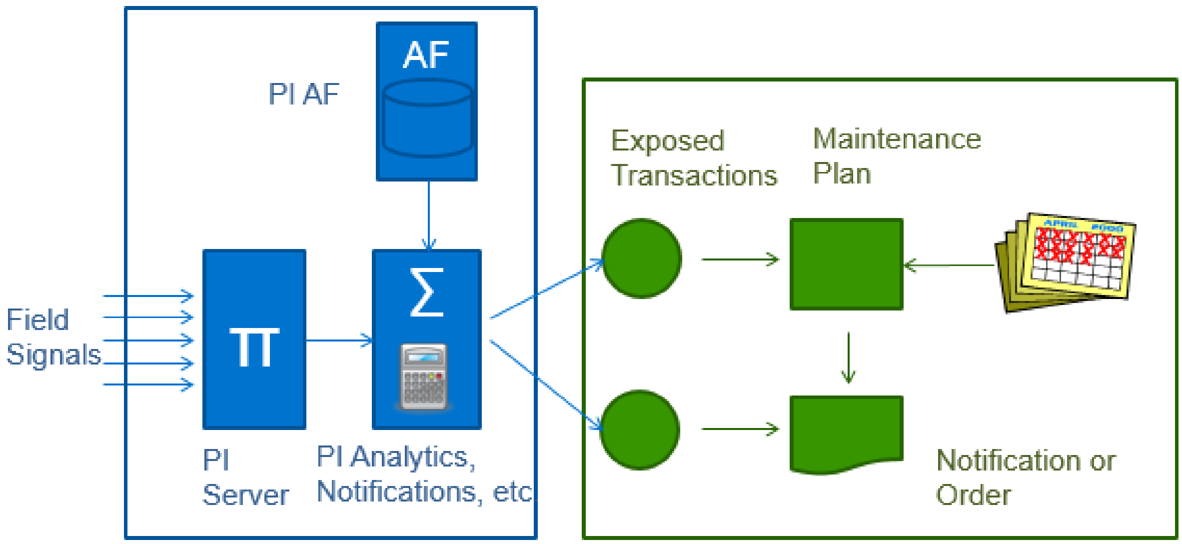


Figure 30 - Conceptual approach to integration of real time data with CMMS

Integration methods comprise the following scenarios:

1. PI System as a real time bus, accessed via the CMMS directly (pull)
2. PI System as a real time bus, using middleware (for example, EAI broker) for integration scenarios with CMMS (push/pull)
3. Windows PowerShell and PI SDK as a programming environment, invoking services of the CMMS for integration (push)
4. PI Notifications, using a delivery channel (OOTB XML or otherwise (push)

For each of the above there are variants. More than one approach may be employed for a given customer for a variety of reasons. For example, in scenario 2 the PI System may use a scheduled program to write into the middleware broker (for example, JMS queue), which would make it a "push" interface.

Often the deciding factor in determining integration with CMMS applications for CBM purposes comes down to organizational preferences. Many organizations have standards for middleware, for integration to EAM/ERP, or preferences of configuration over coding. Preference, skill set and cost factors may complicate the decision more than the technical approach.

5.1 PI System as a Real Time Bus, accessed by CMMS directly

In this method, the CMMS uses an internal program to access PI System data directly via one of the PI Data Access components and may require a client side install (in this case the CMMS program) for the PI SDK, PI WebAPI, PI ODBC/JDBC or PI OLEDB. The CMMS may also invoke remote web services to read/write PI System data or use PI System access components such as PI Web API, PI ODBC or PI OLEDB Enterprise.

The purpose of the Data Request program is to monitor the PI System for process changes that should be reflected in meter updates, and then make those meter updates. This program could also interrogate the state of the maintenance order to reset counters in the PI System, or event frames that indicate work is needed to initiate the next event frame.

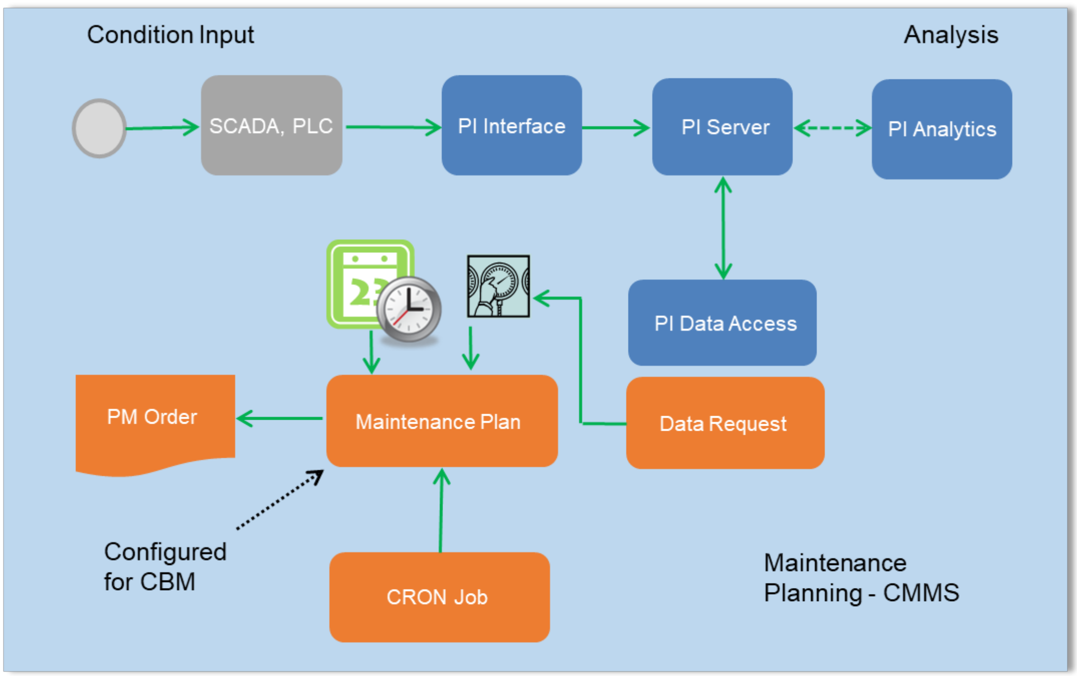


Figure 31 - PI as a Real Time Bus accessed by CMMS directly

The above is a simplistic example and has many variants. It requires a minimum number of PI System components and is supportable by older versions. For example, an SAP ABAP program could control the interface between the PI System and CMMS Meter updates. This program could also generate orders or notifications immediately if necessary.

There are cases where some PI Analytics components are required, including PI Asset-Based Analytics or PI ACE in older implementations.

The following table lists some pros and cons of this approach:

PI System as a real time bus, accessed via the CMMS directly (pull)	
PROS	CONS
Approach suitable to minimal PI System component installations	Requires custom coding on the part of the CMMS support group
Simple to implement in most cases, depending on skill set of CMMS support	Limited configuration information could become an issue to maintain
Programming inside of CMMS allows for extension of features since exposure to most CMMS functions are available	Must be calendar scheduled and may experience some delay in critical notifications.

5.2 PI System as a real-time bus, using middleware for CMMS integration

This method is similar except the task of orchestrating the integration is handed off to an Enterprise Application Integration (EAI) broker or similar middleware.

In the case of middleware, there is typically an adapter involved to communicate with each system involved in a process. In some cases, the middleware may be a part of the CMMS stack (for example, with more advanced EAM/ERP applications).

Middleware allows interaction with the PI System to be scheduled (pick up a summary of data daily) or driven by a CMMS event (work completed to reset notification in the PI System). In either case, the middleware broker would access PI System data using PI Data Access.

The PI System could also initiate the transfer using PI ACE or PI Notifications, or a simple MS PowerShell script. Using one of these methods would support the event-driven architecture of condition indicator changes. For example, should a condition indicate an immediate need for maintenance, the PI System could invoke a function in the middleware to create an order in CMMS.

Functions available to the PI System are limited to those exposed via middleware. The connection to middleware would either be programmatic and custom using PI ACE, or open through web services (using PI Notifications), depending on the middleware technology employed.

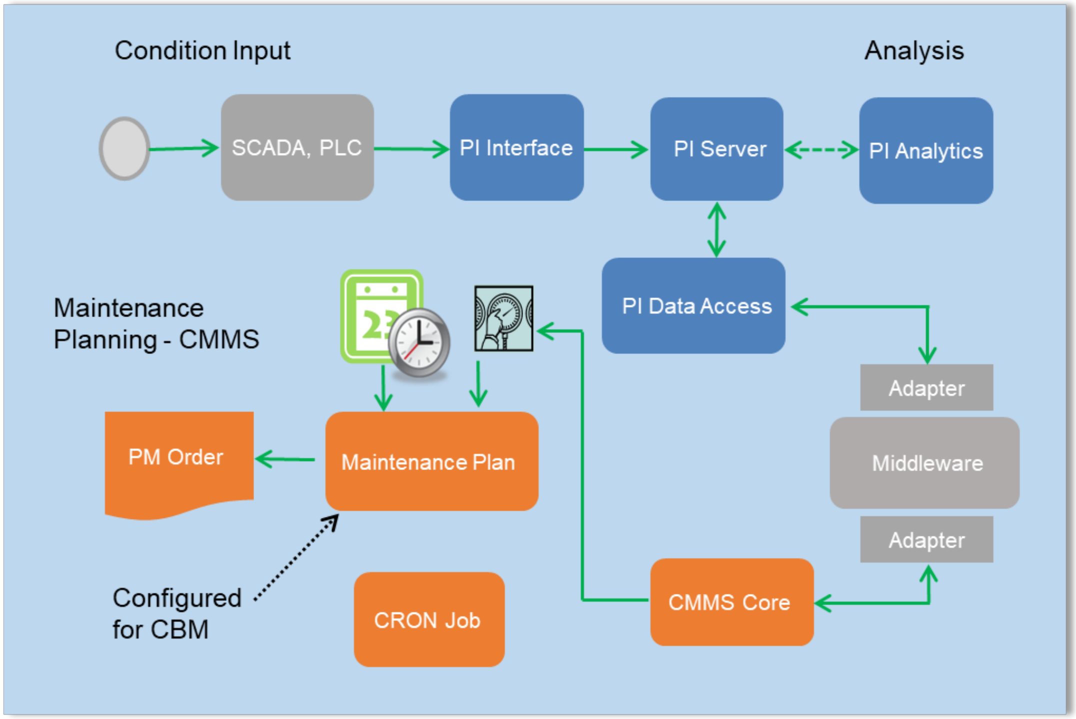


Figure 32 - Integrating PI with CMMS via Middleware

An example of an integration scenario initiated by an event in CMMS is an asset change (location, equipment or component). When this change occurs, it initiates a process that updates PI AF to reflect the asset change. This could be new, out-of-service, retired or changed asset information.

Some examples of common middleware components include:

- IBM Websphere MQ Series – This is IBM's offering for enterprise integration and is a java environment. Typically, web services are invoked, or entries added to JMS Queues, ensuring message communication.
- Microsoft's BizTalk – This Microsoft offering operates in the MS Windows environment and is a very popular and intuitive tool.
- SAP's Process Integrator (PI)– This is SAP's primary EAI broker (formerly XI) and integrates very easily into SAP business processes. It is not limited to SAP integration although it is rarely used outside an SAP enterprise.
- SAP's MII - This is not exactly an integration broker; however it is commonly used as such in SAP Manufacturing enterprises. Manufacturing Integration and Intelligence (MII) is a part of the SAP NetWeaver stack and specifically intended to integrate shop floor systems with SAP and provide analytical and real time displays.

The following table lists some pros and cons of this approach:

PI System as a real-time bus, accessed via the CMMS directly (pull)	
PROS	CONS
Flexibility when the PI System needs to be interfaced to many other systems because it is standards-based	Requires a PI System-specific adapter that supports specific functions
Standards-based when middleware is used for integration scenarios	Limited functions as the solution is based on specific functions

5.3 PI Analytics invoking services of the CMMS for integration (push)

In this scenario, PI Analytics (or similar) operates based on PI System events or clock schedules to invoke the integration process with the CMMS. The integration method could vary depending on the enterprise and technology preferences (custom program, custom data reference or simple MS PowerShell scripts. Integration (shown as a connector in Figure 33) could include:

- Invoking a web service
- Updating a database using an OLEDB provider or update a JMS queue
- Invoking an update to CMMS through a middleware adapter
- Programmatically invoking an update to CMMS, using an SDK or calling an SAP RFC

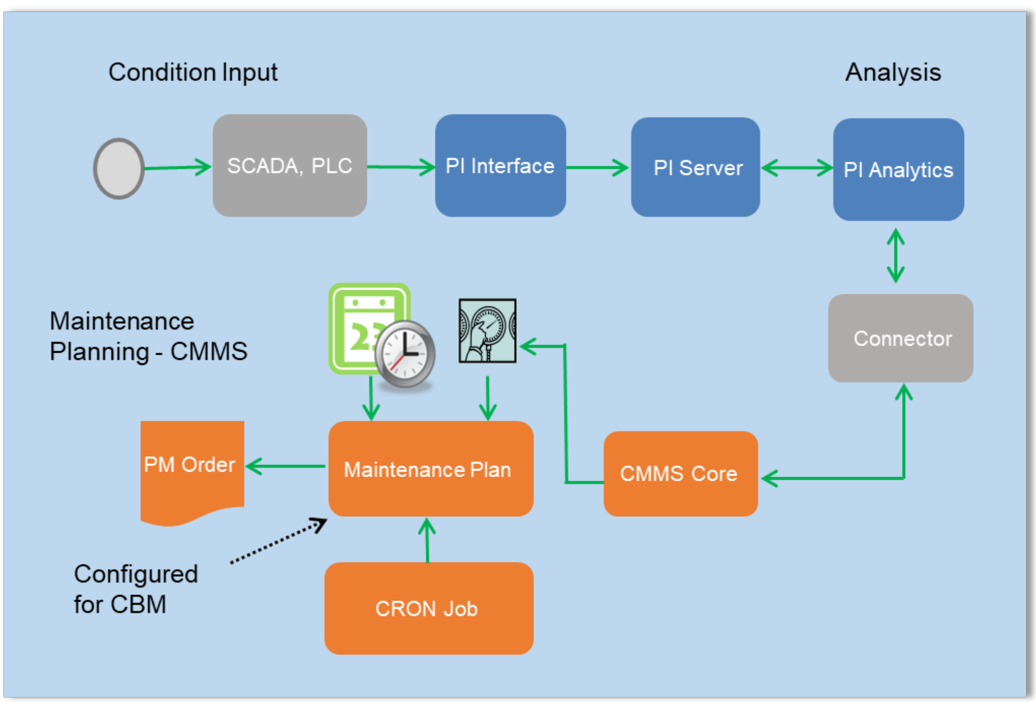


Figure 33 - PI System Integration with PI Analytics

The Connector shown in Figure 33 illustrates custom code that invokes the integration into a 3rd party system. This may be a custom data reference, MS PowerShell script or something similar.

The following table lists some pros and cons of this approach:

PI Analytics (or similar) as an on-demand integration method (push)	
PROS	CONS
Suitable to minimal PI System component installations	Requires some customization of code, which may be as simple as invoking a web service
Simple to implement in most cases, depending on skill set of CMMS support	Limited configuration information could become an issue to maintain
Programming inside of CMMS allows for extension of features, since exposure to most CMMS functions are available	

6 Enabling opportunities

Once the PI System infrastructure has enabled condition monitoring (CM) and CBM through process information and condition indicators, there are many additional opportunities for business value including:

- lifecycle extensions
- decision support
- engineering desktop (system health indicators)
- improved operations
- work prioritization
- more focused capital expenditures
- enabling more effective business intelligence (BI)
- improved efficiencies in root cause and other failure analysis efforts

6.1 Lifecycle Extensions

The PI System provides insights into asset history and associated process history, such as thermal cycling, pressure cycling, event occurrences (for example, high vibration and shutdown). This information can be useful in determining actual equipment life remaining. For example, IEEE provides a standard method to calculate useful transformer life available based on asset process history, load duration curves, thermal effects and current testing results.

6.2 Decision Support

In general, the more information we have about an asset the more effective decisions we can make. Surfacing condition information and asset health indicators to a wide variety of business users can positively affect business outcomes. Decisions can be operations-based, such as what equipment to run based on current condition and run-hour or start/stop history, or what loads to allow on a transformer given its condition.

Condition information can also inform maintenance and reliability engineers in servicing equipment and in better understanding which maintenance procedures are effective and which are not.

6.3 Work Prioritization

Health indicators derived from CBM solutions can also be used to prioritize work related to specific assets, system or processes. If similar work is planned on assets serviced by similar resources, the health of the asset or system can be employed to determine which maintenance to focus on first.

6.4 More focused Capital Expenditures

Historical insights into the health of assets, either specific or by asset type (for example, manufacturer and product code), can be used to focus capital expenditures into resources that will provide the most return on this investment.

6.5 Enabling more effective BI

Many businesses rely on time series data as a source of business-critical operational insights. The PI System provides windows into asset information that you can combine with other process and business information to inform wider business decisions.

In-depth analysis (including multi-dimensional analysis) of asset condition, nameplate and classification information can provide critical insights. Static nameplate and classification data may be maintained in AF, and available to business intelligence tools such as MS PowerPivot.

This information along with time-series data aggregations may also be exposed to reporting and analytical environments using PI OLEDB Enterprise or one of the PI Integrators. Scheduled jobs can move some PI System data into another reporting platform such as MS SQL Server Reporting Services using readily available database tools such as MS SQL Server Integration Services (SSIS).

PI OLEDB users can quickly aggregate vast amounts of interesting data (facts) based on user-selected criteria (dimensions) to identify business opportunities.

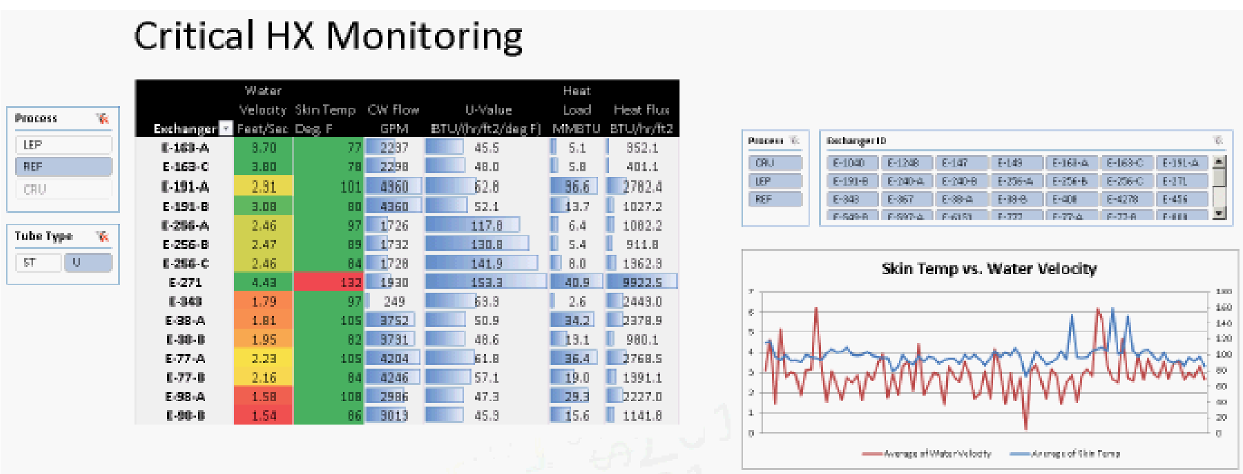


Figure 34 - Quick, ad-hoc BI analysis using PI OLEDB Enterprise

Cubes for multi-dimensional analysis are relatively simple to generate using modern BI tools, and with adequate knowledge of your assets and processes. Figure 35 is an example of a cube organized by facts (gas rate, gas volume and fuel ratio) and sliced by dimensions (equipment type, plant, process and time).

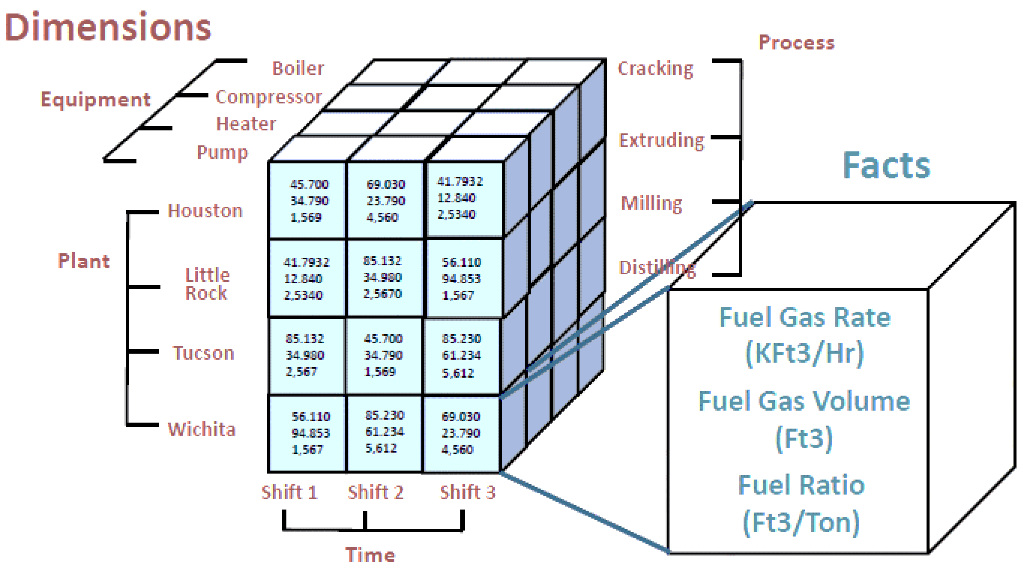


Figure 35 - Multidimensional analysis cube example

7 CBM Solution Examples

This section describes some ways CBM applies to a variety of common asset types. For each asset type, we provide examples where one or more condition indicators are integrated with a maintenance plan or immediate notification. Actionable output will include visualizing the problem and data mining to determine or verify the root cause.

Types of actionable outputs may include:

- publish KPIs and operational metrics (normally through websites and portals)
- email or text notifications
- work order to a work flow engine, such as CMMS, ERP and MES
- generate a detailed fault report
- SOA request into an Enterprise Service Bus (ESB)

These examples are not intended as definitive CBM examples. You can find white papers for each asset represented here with different approaches. A few customer examples and published white papers are listed for additional information and ideas.

7.1 Transformers

7.1.1 Transformer Asset Overview

The average age of large power transformers in the U.S. is approximately 40 years, with 70% being 25 years old or older; therefore a great many are nearing their expected end of life. Many companies are now unable to obtain transformer insurance since the devices exceed their Gompertz life cycle estimates. Copper and iron losses, a natural part of the aging process, are continually increasing the power loss over time in these transformers. CBM can help identify critical assets that need to be replaced before they impact availability or safety.

Unexpected transformer failures can cause significant losses to supporting assets and facilities along with the potential safety risk. Replacement costs for a large transformer easily run into the hundreds of thousands of dollars, and damage to downstream equipment during transformer failure is common. Lead time for transformers is getting longer, with some devices requiring many months for delivery. Outages caused by the loss of a distribution transformer would have such severe impacts that many companies maintain online backup transformers or replace working transformers long before they reach end of life. Either of these strategies is extremely capital intensive and energy inefficient.

7.1.2 Transformer Monitoring and Analysis

Increasingly, transformers are having more online condition monitoring instrumentation equipment installed and used to collect data at the substation and sent back to the central office via substation monitoring, the Energy Management System (EMS), or by other methods (for example, dial-up, dedicated systems, 3rd party pathways to cloud-based solutions). Online monitoring offers the option for onsite personnel to access the data even if there is a loss of connectivity to the site. Regardless of the specific architecture, having consistent access to the data remotely is essential for effective CBM implementations as most installations are geospatially disperse and would be costly to manage through manual inspections.

Having online monitoring information in the PI System means that it can be combined with other information such as loads, ambient temperature, nameplate ratings, and top oil tank temperatures. Combining the diagnostic oil information with these other parameters helps to ensure early detection of issues and correlate incidents such as overheating with excess wear and damage.

Figure 36 represents a simplified fault tree for large power transformers. Typically, multiple condition indicators are monitored on these devices. The most common include load values, temperature sensors and dissolved gas analysis (DGA) monitors.

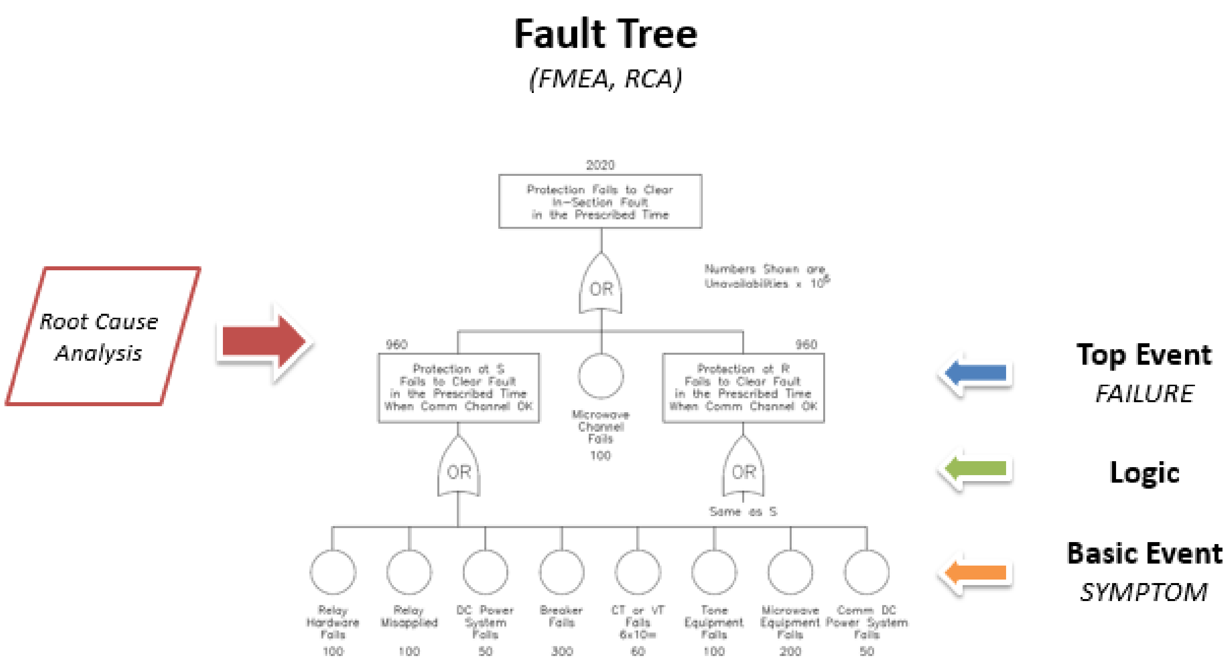


Figure 36 - Example fault tree for large transformers

7.1.2.1 Transformer Oil and Gas Analysis

Transformer oil analysis evaluates water and gas content within the oil and can indicate a possible degradation of winding insulation. Monitoring key parameters from the results of these tests can show when a transformer or its oil need maintenance or further diagnostics. Manufacturers provide guidelines for refurbishment or replacement for transformer oil impurities. Some transformers have gas detectors or Buchholtz relays (usually on conservator models) or pressure relays, which detect high or rapidly rising pressure levels that trip a protective breaker relay on the transformer.

Online or offline tests can be conducted on the dielectric oil of the transformer. These values can be stored as an asset attribute, used to initiate action before a breaker trip event.

7.1.2.2 Online Monitoring for Sweeping Frequency Response Analysis (SFRA)

Methods for offline testing transformers are well established. The Doble test and the impulse response method developed at Powertech Labs in British Columbia have been used successfully for several years to analyze the current state of a device. However, each of these methods requires the transformer be taken out of service and isolated from the surrounding circuits. This is simply not practical for many installations.

Online monitoring of gas analysis, oil levels and temperatures has been practiced for some time now. Unfortunately, the correlation between the analysis results and actual transformers failure modes is relatively low, and the information does not predict failure far enough in advance to plan for the consequences of device outage.

Using a relatively new, high-speed, high-resolution meter called *phasor measurement units* (PMUs) ,transformer health can be calculated online in real time based on two fundamental measurements:

- Sweeping Frequency Response Analysis is based on the delta between a Fast Fourier Transform (FFT) analysis of the transformer input and a corresponding FFT of the output. Statistical Quality Control (SQC) methods are used to determine if the frequency response of the transformer is changing in a meaningful way.
- Complex Impedance Analysis uses the high resolution voltage and current information provided by the PMUs to compute the impedance matrix of the transformer in real-time. Again, SQC methods are used to determine if the impedance of the transformer is changing in a meaningful way.

Both analyses are indicators of structural changes in the transformer that occur on a very small scale. The rate and magnitude of change observed is proportional to the rate and magnitude of transformer decay.

What is unique about this approach is that the alerting is based on rate of change away from observed normal operating conditions, as opposed to waiting for an abnormal condition to occur. Once an abnormal condition occurs (such as a high oil temperature), it is often too late to deal with the situation in a proactive manner. Slope-based alerts indicated a trend towards a problem rather than a problem that has already occurred. Operators have more advanced warning of transformer failure and can make it easier to make plans to repair or replace the transformer.

Real time online transformer health monitoring can be constructed using off-the-shelf OSIsoft PI System components:

1. C37.118 and Arbiter 1344 interfaces collect the required data from the Phasor Measurement Unit meters.
2. The PI Server routes data to all analysis routines and visualization clients in real-time and stores both input and calculated data in the PI Data Archive.
3. The OSIsoft FFT (Fast Fourier Transform) Interface computes the fast Fourier transform of the system frequency at both the inputs and outputs of the transformer in real-time.
4. The PI AF Analysis Service (or custom programs using AF SDK) is used to calculate the complex impedance matrix of the transformer in real-time.
5. The PI-SQC system compares the computed values against statistical norms.
6. PI ProcessBook and PI Vision provide real-time and historical information in graphical formats.
7. PI DataLink and DataLink for Excel Services allow the integration of real-time and historical data into Excel for complex analysis and presentations. PI Vision has extension capabilities that can also provide these displays.
8. PI AF, Event Frames and Notifications provide a rich method for organizing the large volumes of data generated into an easy to understand and manage asset-based structure. Alerting and notifications are then driven directly by this structure.

PMUs are no longer separate, dedicated, expensive devices, and most modern relays include PMU functions. Synchrophasor data from both sides (high and low, or primary and secondary) of the transformer and the PMU data must be time-synchronized with a GPS informed clock for the monitoring method above to fully function.

This approach provides continuous online monitoring of SFRA and complex impedance tests in real time for very valuable and critical transformers. The benefit is continual insight into transformer condition without removal from service for lengthy, complex tests.

7.1.3 Transformer Load Tap Changers (LTCs)

LTCs are some of the most frequently operated devices in the Transmission and Distribution system. Mechanical motions often are primary causes of failure, hence most condition monitoring technology is focused on rotating equipment.

7.1.3.1 LTC maintenance

Typical vendor recommendations for Load Tap Changer (LTC) preventive maintenance are based on LTC operations as opposed to calendar events. Accumulating LTC counts can provide an indication to a counter-based maintenance plan that can drive an LTC PM. Excessive operating counts can indicate circuit activity that requires additional investigation to determine its cause and to remediate.

7.1.3.2 LTC not through zero

Another typical issue occurs when an LTC has not gone through its neutral position over a significant time period. The failure to go through neutral may indicate an imbalance in the network which needs to be investigated and remediated. There may be options for addressing this situation if condition indicators notify appropriate personnel to assess why the LTC has not gone through neutral, or to recommend prescriptive maintenance (for example, capacitor banks switched in or out, LTC adjustments).

The condition to be monitored is a defined period within which the LTC has not passed through neutral (also referred to as zero). A simple calculation can detect this condition in the PI System. When the defined time period elapses an event frame is created, a PI Notification emailed and a maintenance trigger can be sent to CMMS.

7.1.4 Transformer Actionable Output

In addition to data mining or visualizing primary data sets, conditional logic and/or business rules are applied to prioritize and filter automated maintenance requests. Business rules for maintenance and service requests can be very complex. They can also account for the associated risk of non-action and how critical the asset is to the business. And they may also consider warranty status, average lead time or number of inventory spares in their rules to define actions.

Asset-based analytic calculations and conditional logic can be created and applied consistently in a PI System Asset Framework (AF) template. Complex business rules can be applied from asset management or CMMS applications, or in an orchestration engine. For example, if a transformer condition indicates it needs inspection within seven days of a pre-existing maintenance appointment, the system should not create another service request.

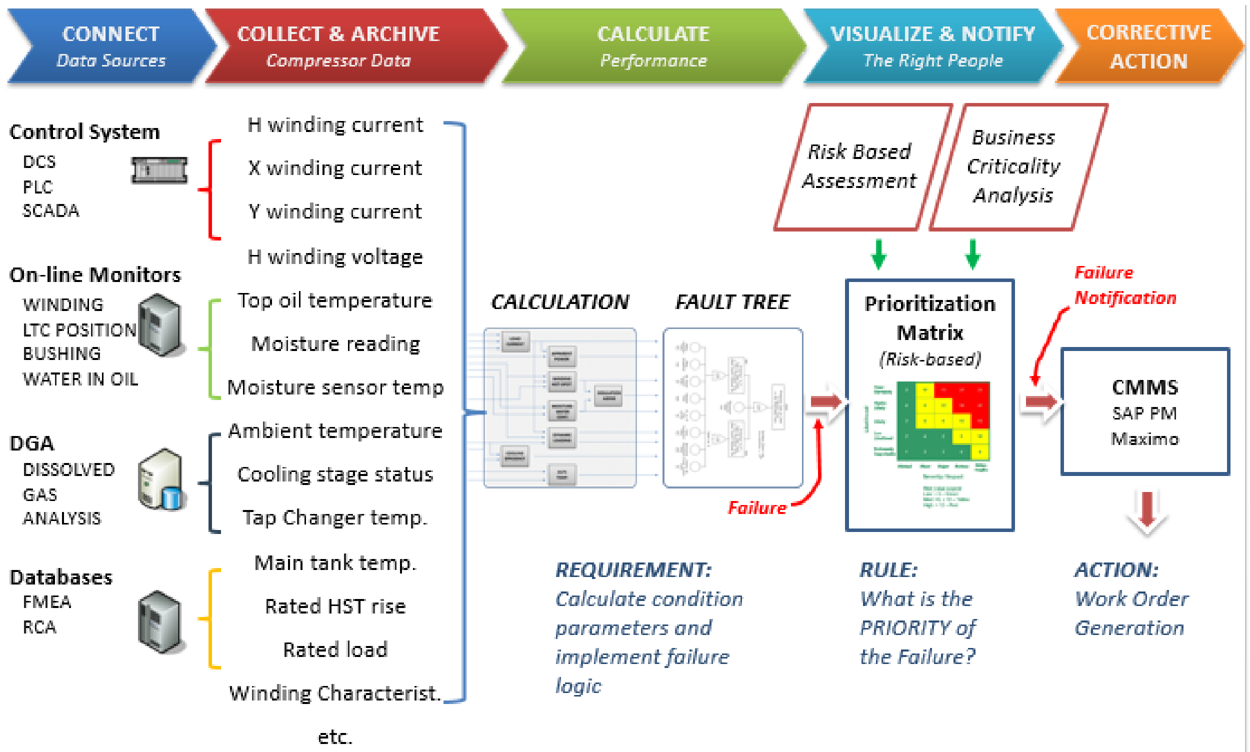


Figure 37 - Transformer Monitoring: Source Data and Process.

In Figure 37 above, some typical process and nameplate values are configured in a PI AF template. Analytics defined within the AF template calculate specific asset health conditions such as time at emergency ratings, high temperature events, and insulation degradation based on DGA results. This process drives specific immediate actions such as operational or maintenance activities, and can factor into longer term decisions for planning, capital replacement projects, and work prioritization.

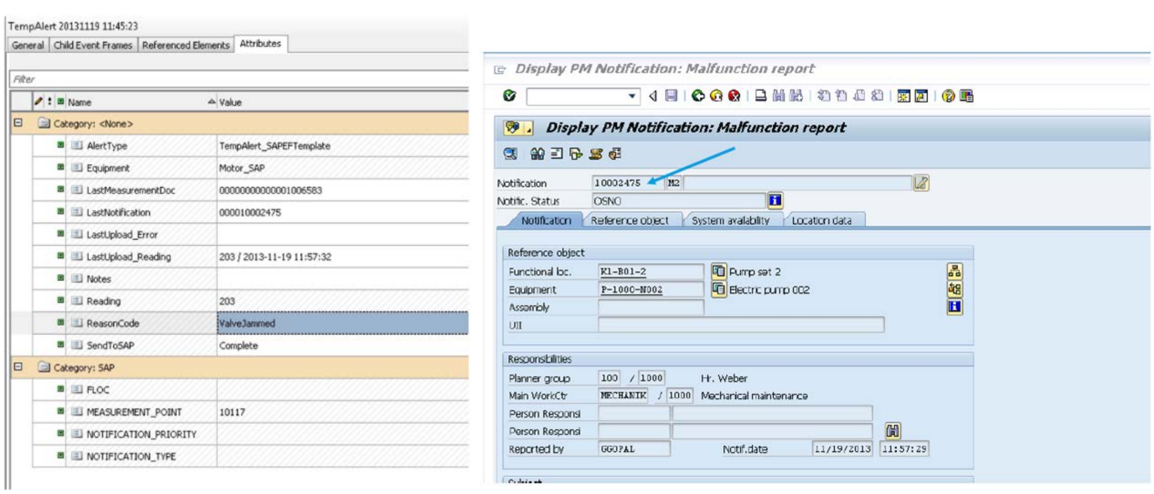


Figure 38 - Example of a PI Event triggering an SAP PM Malfunction Report

7.1.5 Transformer References

Below is additional detail on condition monitoring references for transformer devices. Most of these examples are for larger transformers the size of those in substations, or used as main and step-up transformers at power stations.

- AF Example Kit for substation transformer monitoring
- Alectra (formerly PowerStream) presents on their overall CBM initiatives for substations, including transformers
- Fingrid provides a template for building a condition monitoring system with PI AF

7.2 Pumps

7.2.1 Pump Asset Overview

Pumps are the second most common machine in the world; however, the potential of pump CBM as a source of improved productivity and reduced costs is often overlooked. Because companies utilize numerous types of pumps, creating a standard maintenance strategy can be perceived as an intimidating task. However, a standardized approach leads to a variety of improvements including:

- more efficient operations (operating close to the best efficiency point (BEP) of the pump)
- prolonged asset life (through more effective usage patterns)
- improved capital expense programs (by better equipment sizing)
- lower energy costs by optimizing energy management
- maintenance improvements (by doing the right maintenance at the right time, moving from unplanned to planned activities)

The following is an approach to leveraging the PI System to create a standard, scalable monitoring solution for an organization's centrifugal pump assets.

7.2.2 Pump Monitoring and Analysis

A principle challenge to creating an effective system for pump maintenance is provision of a systematic framework to link static pump properties, high fidelity operational data and operational context. Examples of attributes, data streams and events that should be brought together so that users can see asset information in context are:

- Manufacturer
- Type
- Size
- Horsepower
- Available Net Positive Suction Head ($NPSH_a$)
- Required Net Positive Suction Head ($NPSH_r$)
- Static head
- Friction loss
- Process
- EQ number
- BEP (TDH, Efficiency, 80%, 110%)

- Pump On/Off Pump run hours
- Pump start/stop number and frequency
- Motor temperature
- Flow rates and pressures (in, out)
- Screen differential pressures
- Vibration Monitoring points
- Bearing Temperatures
- Motor current signatures
- Visual inspection results
- Motor power (kW)

Having this information in the PI System means that pump data can be organized according to asset attributes and topology. The PI Asset Framework (AF) creates a template for a basic pump that includes available information that applies to most pumps. This information includes nameplate data, maintenance data, date installed, Best Efficiency Point (BEP), criticality to the process, and next maintenance date. Once templates are populated with data streams, calculations and static data values, users have access to a single, consistent method to shape and prioritize pump maintenance. This is a significant business improvement as CBM implementations are more costly to manage through manual inspections.

For example, users can track the run hours or basic conditions related to the operation and maintenance of the pump. When pump issues or failures occur, historical data can be analyzed to develop condition indicators and link root cause to vendor, use conditions or external conditions. Once this first phase is complete, consider a more robust strategy of incorporating alarm data and integrating the PI System with a CMMS system (to drive a true CBM solution).

An example is when pump run hours approach the vendor-specified limit for maintenance or calibration. Operators can use PI System to define a trigger that creates a work order in the local CMMS system. When this work order is complete, a message can be returned to reset the run hours counter on the asset.

Condition monitoring (CM) of pumps alone can lead to improvements in operation and maintenance and is a first step to true CBM. CM may be accomplished using operational data, condition specific data and eventually lead to information that serves as the basis for other predictive techniques such as advanced pattern recognition (APR) that can be particularly useful in pump maintenance.

7.2.3 Pump Actionable Output- Visualization

A key part of an effective PM solution is to develop accurate condition indicators and methods to display actionable asset condition information. The PI System provides visualization options that can be reused, shared throughout the enterprise, and easily modified as operations and data needs evolve. Operators can use real time displays to monitor asset condition within any maintenance strategy. Users can create standard visuals of the pump data for multiple end users using tools like PI ProcessBook or PI Vision, as seen in Figure 39.

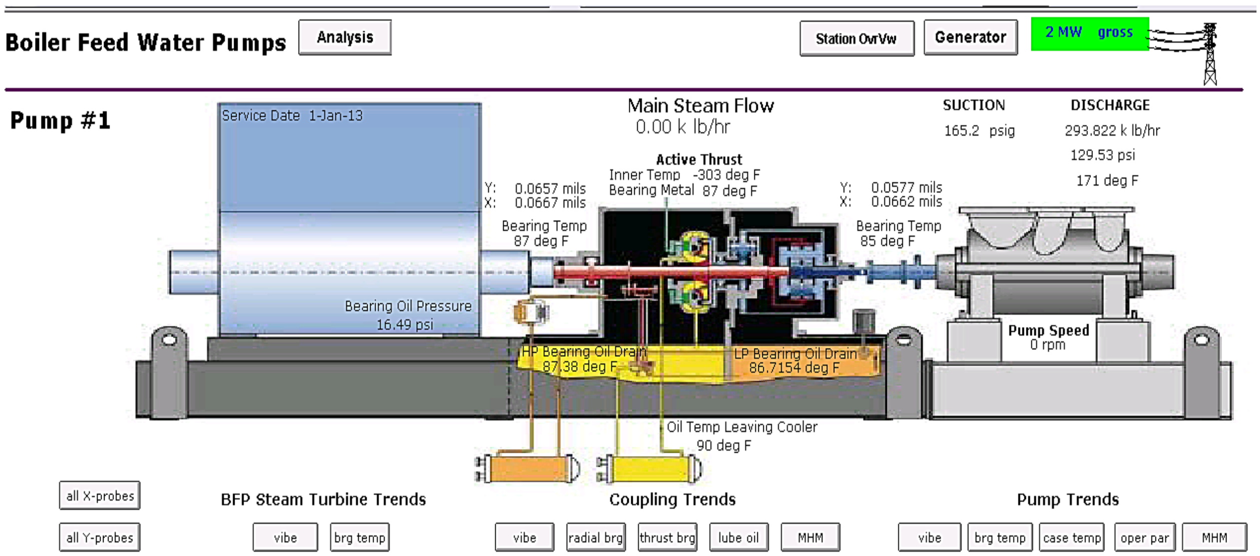


Figure 39 - Sample Condition Monitoring Display from PI ProcessBook.

When organizations use OSIsoft's Asset Framework to structure asset data, operators, maintenance or engineers can toggle between views of different pump assets associated with the same AF template. Over time, they can determine how different vendors' pumps perform, or how much one costs to maintain versus another. They do not have to create custom graphics or calculations for each pump, simplifying the creation and maintenance of the data management system.

Maintenance and engineering personnel can drill down into archived condition monitoring data for analysis. Engineering can conduct root cause analyses, develop more precise indicators to optimize CBM solutions or create information for equipment replacement evaluation. In some cases, maintenance may need access to this information to evaluate what maintenance to perform and when to perform it.

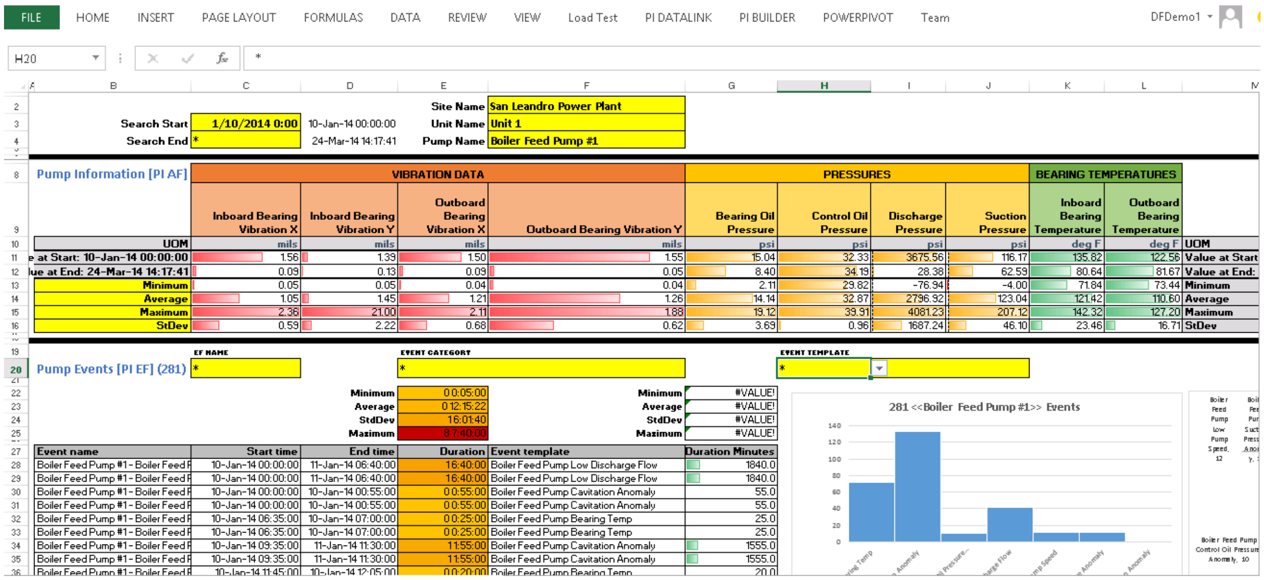


Figure 40 - MS Excel BI Condition Monitoring Report using PI DataLink

Real time online health monitoring for pumps can be constructed using off-the-shelf OSIsoft PI System components:

1. Standard PI System interfaces collect the required data from the pump motors, bearings, flowmeters, and so on. These typically come from PLC's, DCS or SCADA interfaces.
2. The PI Server routes data to all analysis routines and visualization clients in real-time. It also stores both input and calculated data in the PI Data Archives.
3. PI Asset Framework organizes pump data according to asset attribute, elements and topology to create a standardized method of assessing pump health.
4. The PI Asset Analysis Engine (or custom programs using the PI AF SDK) is used to calculate condition indicator values in real-time.
5. The PI-SQC system compares the computed values against statistical norms.
6. PI ProcessBook, PI DataLink (Figure 41 shows examples of PI Datalink reports) and other client tools display real-time and historical information in visual and graphical formats

7.2.4 Pump References

More detail on condition monitoring for pumps is included below. Most of these references are for larger pumps, those in critical processes of larger asset industries.

- Millenium Inorganic Chemicals used the PI System out of the box to do pump CBM
- San Francisco Public Utilities Commission (SFPUC) and their CBM implementation focused on pumps and integration with Maximo
- An AF Example Kit for CBM with Pumps
- Las Vegas Valley Water District used the PI System to calculate pumping efficiency and predicting maintenance on pumping stations

7.3 Compressors

7.3.1 Compressor Asset Overview

Compressed air, along with gas, electricity, and water, is essential to most modern industrial and commercial operations. It runs tools and machinery, provides power for material handling systems, and ensures clean, breathable air in contaminated environments. Operations use compressed air in virtually every industrial segment from aircraft and automobiles to dairies, fish farming, and textiles.

Often plants consider the expense of compressed air only in terms of equipment cost. Energy costs, however, represent as much as 70% of the total expense in compressed air production.

7.3.2 Compressor Monitoring and Analysis

Figure 41 provides a basic overview of sources of data relevant to compressor health and monitoring.

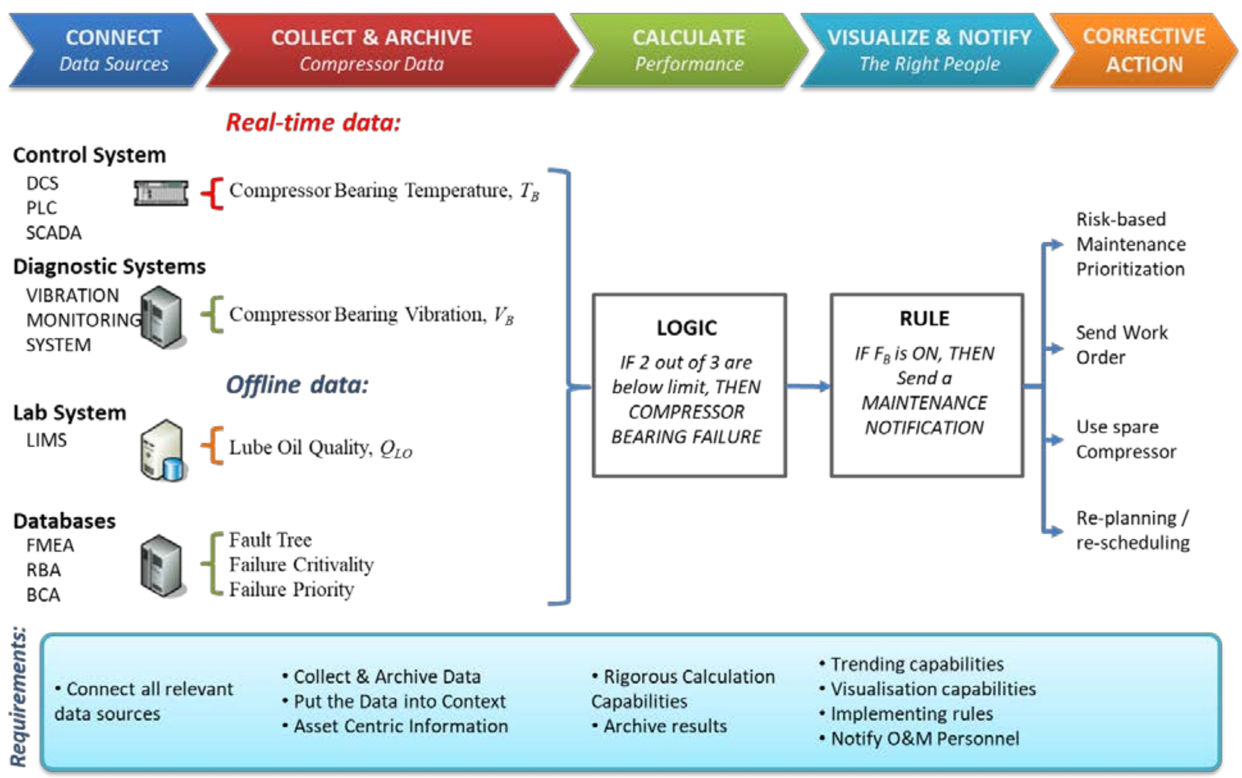


Figure 41 - Compressor Data and Maintenance Condition Monitoring

7.3.3 Compressor Actionable Output

In this example, a report was sent to the maintenance department for review and recommendation. This may happen as a function of a business process or in conjunction with other notifications such as CMMS or CRM.

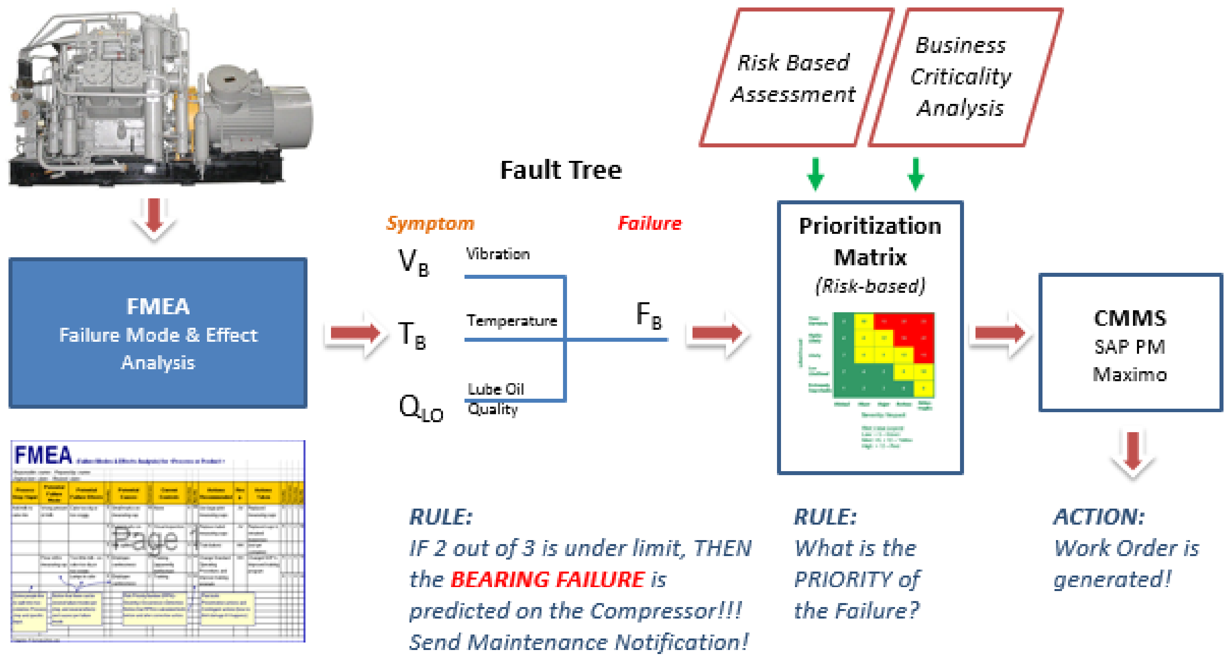


Figure 42 - Example Process Overview for Compressor Asset Health

7.3.4 Compressor References

More detail on condition monitoring references for compressors is provided below.

- How TransCanada uses the PI System and SQC with physics-based models to perform anomaly detection, and make more informed decisions relative to compression equipment
- Columbia Pipeline Group operates reliably through major system events, such as extreme weather, and have prevented many failures based on reliability monitoring with the PI System
- The Compressed Air Challenge™ is a national collaborative formed to assemble state-of-the-art information on compressed air system design, performance, and assessment procedures
- Gas Turbine Health Monitoring system to monitor compression equipment health for a natural gas pipeline in China
- Achieving Reliability Center Maintenance (RCM) on pipeline equipment for Alyeska Pipeline
- Improving compression equipment reliability with Caterpillar condition monitoring services

7.4 Heat Exchangers

7.4.1 Heat Exchanger Asset Overview

Heat exchangers are mechanical devices designed for the transfer of heat from one fluid matter to another through a solid surface. The fluids themselves never mix and are separated by the solid surface. Heat exchangers are widely used in petroleum refineries, chemical plants, petrochemical plants, natural gas processing, refrigeration, power plants, air conditioning and space heating. Other examples of heat exchangers include intercoolers, boilers, condensers and preheaters. You also find heat exchangers in everyday household appliances such as air conditioners and refrigerators. One common example of a heat exchanger is the radiator in a car: a hot engine-cooling fluid like antifreeze transfers heat to air flowing through the radiator.

Typical degradation of heat exchangers includes:

- wall thinning (oxidizing material)
- corrosion and scaling (pitting and build-up of materials)
- dimensional creep (warping and movement due to heat)
- tube fouling

7.4.2 Heat Exchanger Monitoring and Analysis

The actual heat transfer coefficient is used to determine the overall effectiveness of a heat exchanger over time. Real-time models can also calculate the actual tube fouling in a heat exchanger. A more practical method uses a simple calculation to compare the input and output temperatures to provide overall condition assessment of a heat exchanger. Sensors equipped to monitor the process effectiveness can also be used to evaluate its overall condition.

A simple heat exchanger template can be created and applied to more complex assets that may contain a heat exchanger. The asset elements will also allow data roll-up calculations so that each heat exchanger can be compared to the performance of the others, identifying outliers as prospective maintenance targets.

Real time, online health monitoring for heat exchangers can be constructed using off-the-shelf OSIsoft PI System components. There is additional information on how to do this with the OSIsoft provided heat exchanger tutorial.

7.4.3 Heat Exchanger Actionable Output

One effective way to make CBM information actionable is to send a notification to responsible parties when an important event has occurred. In this example, a heat exchanger has degraded to a point where it needs attention. In addition to sending a maintenance request to a CMMS system, the PI System will send an email to the maintenance manager on duty, along with links to visualization tools that will provide additional insight on its severity, as shown in Figure 43.

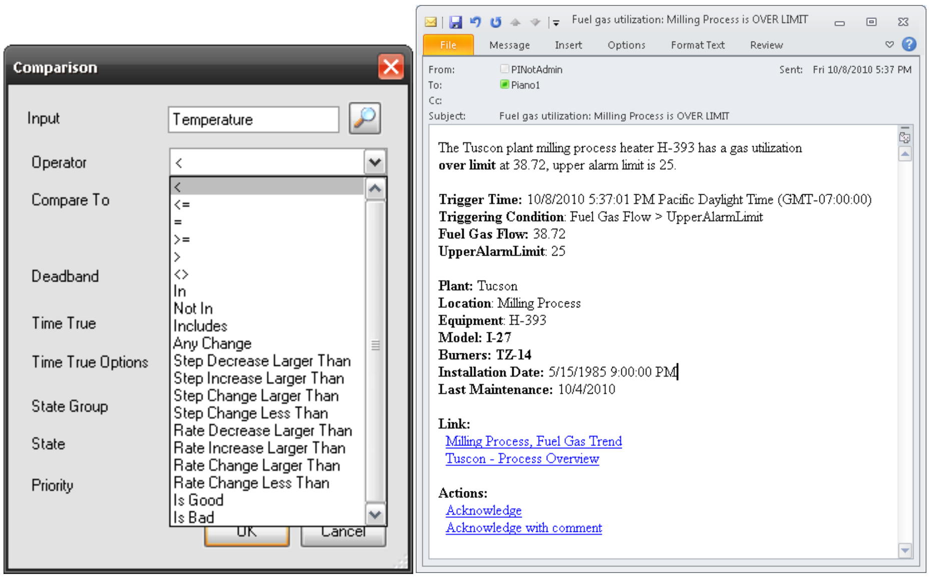


Figure 43 - PI Notification event comparison and email example.

In the event the primary person or group responsible for maintenance is unable to act, PI Notifications can be configured to escalate the issue. The acknowledged time and period counts of the notifications can also be used to benchmark the overall maintenance workload and response times using an Excel spreadsheet add-in client.

7.4.4 Heat Exchanger References

More detail on condition monitoring references for heat exchangers is provided below.

- Development of Real-Time Damage Monitoring System for the Optimization of Inspection Planning of Power Boiler Tubes by KEPCo
- Using PI to Back-Test Usage and Condition Based Maintenance Strategies to Predict Quantifiable Benefits Prior to Deployment in Asset Management by DTE
- OSIsoft has developed a Heat Exchanger Tutorial to demonstrate how to use the PI System to do typical calculations

8 References

This section includes OSIsoft and other industry references.

We highly recommend visiting and searching the OSIsoft PI Square site to find additional information from customers and partners. There is a PI Square community group for maintenance and reliability. PI Square also has groups by industry that may have specific maintenance information relevant to your business.

There is also an online course for CBM with the PI System with additional resource links.

There is an AF Example Kit for general condition monitoring. This kit incorporates typical aggregations and analyses used in condition-monitoring scenarios. It also includes rollup calculations to allow you roll up asset health and conditions from lower tiers of an asset hierarchy to parents.

OSIsoft has training and other valuable information on YouTube, including a video on CBM. These videos provide high level information on the use of the PI System and related videos may be useful too.

8.1 OSIsoft Industry References

Below are some summaries with links to more detail on specific customer references where customers have employed their PI System for condition monitoring and/or CBM.

We encourage you to use the search box on our homepage to search for companies, terms, topics and other items that can help you in using the PI System for CBM.

8.1.1 Power Generation

Continuous reliability improvements in wind power generation from Sandia National Labs discusses their program for wind reliability. Details here.

Improving Nuclear Power Plants efficiency and reliability through advanced monitoring and pattern recognition, by Exelon. Details here.

Scrubgrass Generation used the PI System and a variety of data sources to determine when it was best to operate and when it was best to take downtime to perform maintenance. Details here.

8.1.2 Transmission and Distribution

Sempra Energy (SDG&E) uses the PI System for condition monitoring of substation assets. Details here.

PSE&G uses the PI System as the core component of their CMMS, Foundation for Smart Grid Modernization. Details here.

Alectra (previously PowerStream) is a Canadian utility company that is using the PI System on their path toward intelligent maintenance. Details here.

8.1.3 Oil and Gas

Alyeska Pipeline uses the PI System for implementation of their Reliability Centered Maintenance (RCM) diagnostics system. Details here.

Chevron Brazil enabled condition-based maintenance using the PI System and employed extensive use of Event Frames. Details here.

8.1.4 Chemical

Arkema Chemicals uses the PI System in a wide variety of areas to improve operations and reduce operating costs. They developed a motor current monitoring system for pumps that led to significant costs savings on pump maintenance. Details here.

Dow Corning uses the PI System as a part of their Overall Equipment Effectiveness (OEE) monitoring system and helping to analyze failures to prevent others in the future. Details here.

8.1.5 Metals & Mining

The PI System played a key role in helping Dofasco achieve maximum asset reliability. Details here.

Ultratech Cement uses the PI System for monitoring critical process parameters and equipment condition in real time. Details here.

8.1.6 Pharmaceuticals

Abbott Laboratories deployed CBM including integration with Maximo across their global fleet. Details here.

Baxalta used the PI System for Energy Management and quickly found related value in condition monitoring of critical assets. Details here.

8.1.7 Transportation

Marathon Petroleum Company uses the PI System to monitor marine barges in terms of asset condition, efficiency, fuel usage and safety. Details here.

Barrick Gold uses the PI System to enhance availability and productivity in mining operations, which are impacted by truck availability due to maintenance issues. Details here.

8.1.8 Pulp & Paper

Learn how Weyerhaeuser used the PI System to achieved significant savings in one week on their condition monitoring initiatives. Details here.

Klabin Packaging uses the PI System to better inform operators on critical operating parameters and most effective operations of the plant and assets. Effective use of assets improves asset life and lessens energy expenditures. Details here.

8.2 Partner References

The OSIsoft Partner Ecosphere is an excellent place to find partners and partner solutions. Partner offerings come in several forms including:

- Partner Services – Talented, experienced professionals with both the PI System and asset health and reliability services.
- Partner Products – These are either stand alone or integrated into the PI System to enhance the value of CBM initiatives.
- Partner Solutions – These are 3rd party connected services agreements where customer data is sent to the Partner's platform and the partner can then offer services on the data, such as improving operations and condition monitoring.

We recommend you visit the OSIsoft Marketplace to find the most up to date information on offerings.

DST Controls provides engineering services and has consulted on many CBM projects with the PI System. Details here.

Allied Reliability Group provides engineering services and their own condition monitoring tools and services, to help customers implement condition monitoring with the PI System. Details here.

Process Innovations Inc. offers services, software and connected services related to condition monitoring. They have worked in various industries and have a lot of experience with power generation. They have a set of PI AF add-ins (Process Plugins) which expedite and enhance setup of process equipment in the PI System. Details here.

ECG offers the OSIsoft community bolt-on, value-added application solutions and integration services. One of the ECG offerings is PredictIT, which is an Advanced Pattern Recognition (APR) or model-based tool, to detect anomalies in operating data based on historical profiles. This is one of the partner solutions for APR and it is tightly integrated with the PI System. Details here.

National Instruments (NI) provides powerful, flexible hardware and software technologies that accelerate productivity, innovation, and discovery in nearly all industries. NI has integrated their flexible, open diagnostic platforms such as LabView and InsightCM with the PI System. Details here.

8.3 Published Information

Continuous Reliability Improvement article, Pride in Maintenance website.

In Pursuit of the Perfect Plant, Book by Pat Kennedy, Vivek Bapat, and Paul Kurchina

Reliability engineering principles for the plant engineer, Reliable Plant Magazine

Society for Maintenance and Reliability Professionals – Website

Reliability Centered Maintenance, Plant Maintenance Magazine - Website

Plant Services - Website

Reliability Web and Uptime Information - Website

Association for Asset Management Professionals forum on the Institute for Nuclear Power Operations (INPO) Equipment Reliability Process (INPO AP-913) - Website

IEEE Transformer CBM white papers - search for power transformer condition based maintenance for a complete list.

O&M Best Practices – A Guide to Achieving Operational Efficiency, Issued by the US Department of Energy, July 2004;

8.4 List of Figures used within

8.5 The team that put this book together

We are a team of OSIsoft professionals with industry CBM and PI System technologies experience. We are passionate about bringing value to our customers by sharing solutions based on the PI System. We appreciate your time and hope you have found the content valuable.

Keith Pierce – Global Solutions Group

Gopal Gopalkrishnan – Partner Solutions Architect

Chris Crosby – Digital Transformation Specialist

David Thomason – Industry Principal – Power Generation

Curt Hertler – Global Solutions Group

Matt Miller – Industry Principal - Transportation

Zsolt Oros - Regional Account Manager

Roland Wedgwood– Sr. Technical Writer

Dan Claessens – Manager, Global Content Strategy

8.6 Revision History

Version	Date	Changes
1	March 2015	Initial issue.
2	March 2018	Updated for newer PI System component descriptions. Updated references and better organized them. Clarified the content around model driven strategies or APR. Also made minor updates and changes throughout.