Implementing Condition-Based Maintenance Using Real-time PI System Data

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

OSIsoft.

E-Book

Table of Contents

Table of Contents

1 Introduction

Today, innovative asset management teams are looking for ways to use machine data to balance trade-offs between asset cost, performance and risk; however, it has become challenging to acquire, integrate and analyze data from an ever increasing range of operational sources without creating customized solutions. This eBook provides recommendations for integrating high fidelity operational data when implementing condition-based maintenance (CBM) solutions with popular CMMS[1] application and the 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, PI System users accelerate their ROI from various IT applications, including CBM applications, when the PI System feeds information derived from real time OT data into them.

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
- Capturing and storing 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 values.
- Powerful means to surface asset health information. Information can be consumed in a wide variety of ways 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, PLC, etc. and IT – Informational Technology, typically enterprise business networks and systems such as ERP, eMail, Customer Services, etc.

1 Overview

CBM can be an important component of holistic asset management strategies (described in ISO55001) that improve asset performance, reliability and lifecycle. These strategies establish criteria to prioritize asset management decisions according to organizational needs, defined 'value' and to achieve balance even when faced with conflicting objectives.

As a maintenance strategy, CBM crosses all major industries and asset categories (e.g. rotating equipment, transformers, mining vehicles, fluid management, etc.) It differs from calendar-based regimes in that it leverages asset data to align maintenance schedules with actual asset condition, organizational mission and changes in environment. CBM processes evolve as insights arise and system experts (asset managers, performance engineers, etc.) apply lessons learned to the system in terms of maintenance program changes, analytic definitions, etc. CBM starts with monitoring specific asset parameters, continues with evaluation of that parameter in relation to limits, trends and other asset data. It ends with integration with the work management solution. Through an evolutionary process, CBM programs tie real time data with effective work management systems (Figure 1).

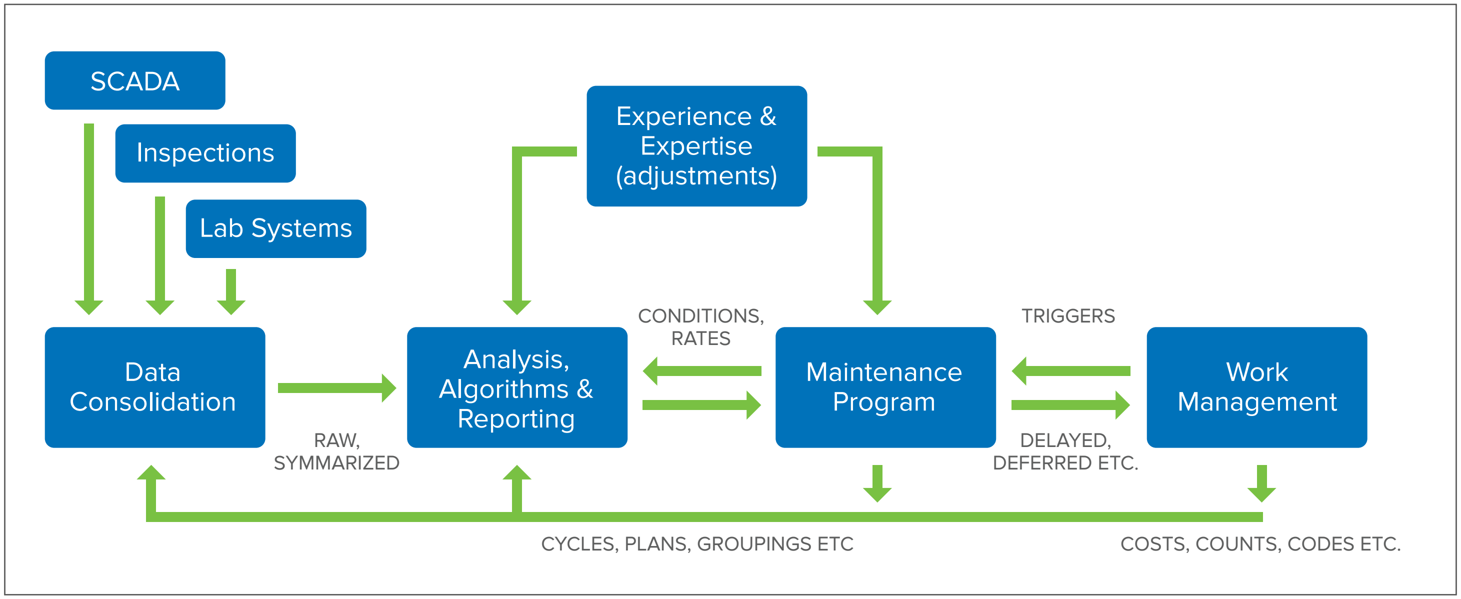


Figure 1: This figure shows the flow of aggregated and event-based real time data fed into a CMMS and its prescribed maintenance activities.

2.1 An Introduction to Condition-Based Maintenance (CBM)

Condition Based Maintenance (CBM) can be defined as a set of maintenance processes driven by real-time asset information to ensure maintenance is performed only when evidence of need exists.

The goal of a CBM implementation is to move from a calendar-based preventive maintenance program to a condition-based preventive maintenance program (Figure 2).

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)
- mprove asset availability (minimize asset downtime)
- Enable value realization from condition information (e.g. lifecycle extension, decision support, better capital expenditures, etc.)

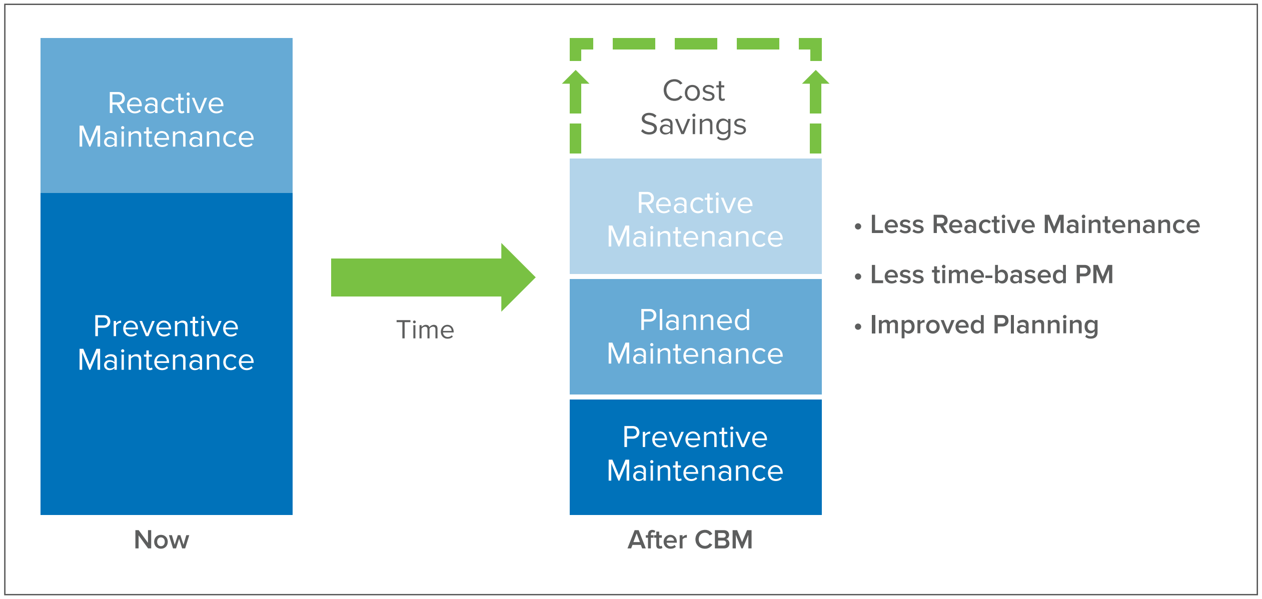


Figure 2: CBM shifts cost and distribution of maintenance activities

2.2 Role of CBM in Computerized Maintenance Management Systems (CMMS)

Maintenance processes normally are, and in the case of this document are assumed to be, managed in a work management system as pre-described maintenance tasks (preventive or planned). Work management systems are typically called a computerized maintenance management system (CMMS) and 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) system.

Maintenance processes have been historically based on conservative calendar (time-based) schedules due to a lack of asset-specific condition information. Calendar-based schedules recommend more frequent maintenance in order to avoid running an asset to failure. Calendar-based schedules can generate unneeded maintenance, increase costs, create maintenance- derived issues and decrease overall asset availability. When asset information is integrated into CBM-enabled work systems, maintenance processes are generated by asset-specific condition indicators.

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

The benefits of well-implemented CBM programs extend outside of protecting corporate investment in asset portfolios. Costs can be planned. (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 creating visibility into asset condition indicators can help prevent catastrophic failures. It only takes a few big saves to typically pay for a complete CBM implementation.

3 Maintenance Strategies & Types

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's 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.

3.1 Strategies

REACTIVE MAINTENANCE is considered a reactive, sometimes "run to failure" strategy where personnel respond to incipient failures. Reactive maintenance is appropriate for some non-critical assets and/or when impacts and costs of failure are minimal.

CONDITION-BASED MAINTENANCE CBM generally applied to a set of critical assets. These assets can have significant repair & replacement costs and/or cause significant impacts to the business process when they fail. Specialized condition monitoring equipment may be required to monitor the condition of assets and respond to trends or events indicating a degraded condition. Current operating parameters, monitored using computing technology, can also be used to drive maintenance plans, derive asset conditions, etc.

OPTIMIZED OR PREDICTIVE MAINTENANCE This third tier of the maintenance maturity model involves using asset data for longer term cross-asset analytics and trends in failure codes, asset conditions, etc. The outputs of these analyses drive improvements to maintenance programs in several ways. They may reveal use- or vendor-specific asset conditions or improve other related maintenance techniques such as training, maintenance task definitions, spare parts inventory, etc. This strategy can also be used to justify capital expenditures for equipment replacements, upgrades and selection of one type of asset or one vendor over another. It also often involves more sophisticated methods of condition determination including advanced pattern recognition (APR), model-based monitoring, multivariate statistical analysis, etc.

3.2 Types

PREVENTIVE MAINTENANCE Preventative maintenance (PM) is a set of prescriptive, pre-defined tasks that accomplish specific preventative maintenance activity. PM usually follows a vendor's PI System for CBM recommendations, regulatory guidance or industry experience. Tasks are done in a proactive manner and assumes that no equipment failure has occurred. Historically, this has been based on calendar or facility events (e.g. outages) and not on condition.

PLANNED MAINTENANCE The maintenance activities are very similar (and often used interchangeably) to preventive maintenance as described above. They are prescriptive, follow recommendations, etc.; however they are generally also referred to as event-based, i.e. they are called for after a specific event, such as a predictive indicator. Preventive maintenance is included in this category.

CORRECTIVE MAINTENANCE These activities are reactive and in response to an asset issue or failure. Except for RTF components, these are to be minimized in most cases due to their cost and impact to operating conditions.

PREDICTIVE MAINTENANCE Predictive maintenance uses condition monitoring and other stochastic methods to try to determine when a future failure will occur. With some predictive maintenance the idea is to perform planned work without reacting to an incipient failure. Predictive maintenance can operate online (e.g. vibration monitoring) or off-line. For example, it's popular to do eddy current testing in steam generator tubes during an outage to determine which tubes should last until the next outage and which ones need plugging.

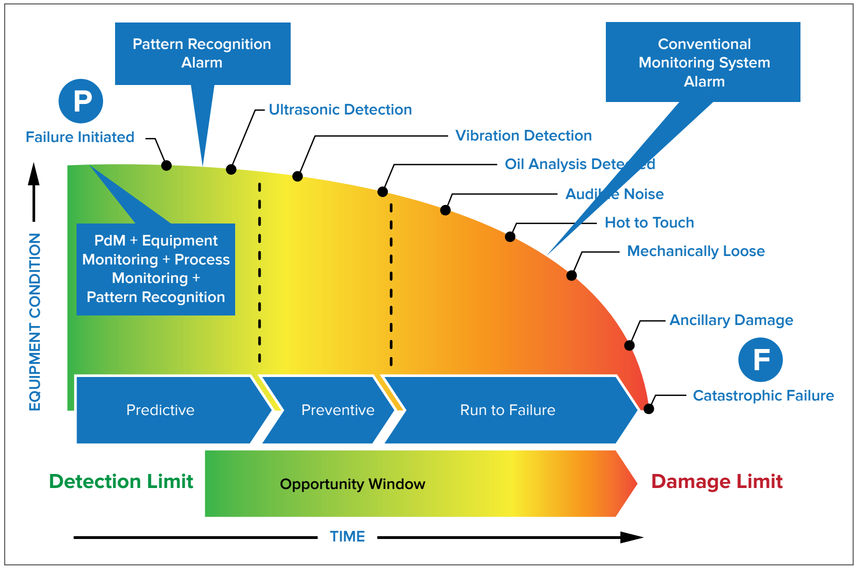


Figure 3: PF Curve used in Predictive Maintenance. The predictive maintenance model uses various techniques to produce a point on a graph to determine remaining life of an asset.

Back to Table of Contents

The “Run to Failure” portions of the graph in Figure 3 represent the risk of asset failure based on results of a test method. The response opportunity time varies based on asset, type of test and frequency of the testing method. Quite often there is little time to respond, depending on plant conditions, time of the notification, etc.

MODEL DRIVEN MONITORING Model driven monitoring is both a maintenance and operations approach to reliability and improved operations. It requires that an anticipated operational model exists for the asset, system, process, etc. for a given set of ambient and input values. Operational models are based on previous experience of a similar plant or system to understand expected behaviour given current conditions. The model will provide anticipated values for process parameters, e.g. temperatures, pressures, vibration, etc.

During operations, displays, alarms, etc. can be setup to monitor the actual values as compared to the anticipated values. Identified deltas lead to awareness of unanticipated asset condition or operation. In typical use, a monitored parameter is checked periodically to ensure it is within in its anticipated range. If a number of consecutive samples all indicate that the monitored parameter is outside anticipated range, then an alarm is latched.

This approach is rather complex, although it can be started on a smaller level by focusing on some critical parameters and then growing it into a model for the complete process. Industry groups (e.g. EPRI), standards organizations (e.g. IEEE) and OEM companies often offer some models for specific assets and systems. Model driven monitoring typically uses advanced pattern recognition (APR) and it may be referred to in this way (Figure 4).

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

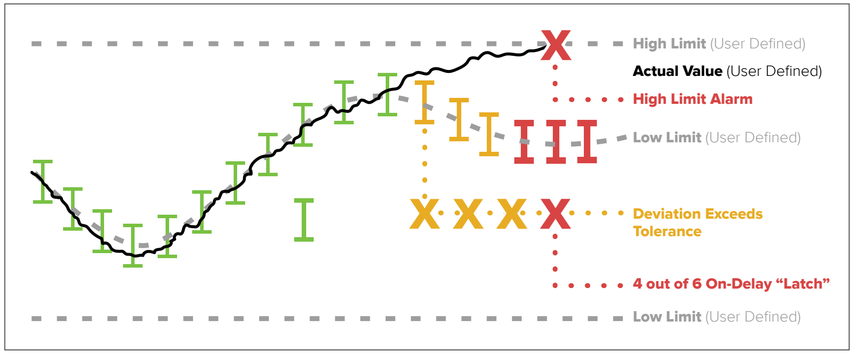


Figure 4: an example of APR in action on a monitored process variable

4 Implementing CBM

4.1 Getting Started

The “getting started” is vital to developing a successful CBM implementation. Because CBM implementation is a process, successful CBM implementations will typically start small and expand over time as process and information becomes more refined. Treating CBM implementation as a project will often doom efforts from the start. To start, identify some asset currently serviced through calendar-based schedules. Some factors to consider while identifying 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 – can help identify assets whose mean time to repair or mean time between failures are out of prescribed ranges.
- Strong business case (ROI) – when cost per failure is high for a particular assets, targeting these assets for CBM presents a strong financial return.

After identifying asset candidates for CBM, the following resources can be used in the pilot implementation:

FAILURE MODES AND EFFECTS ANALYSIS (FMEA) reports should contain indicators of failure methods which may identify key points for condition monitoring (Figure 5).

ROOT CAUSE OF FAILURE (RCF) reports show how smaller issues and their ability to go undetected can result in a major incident. By identifying missing or non-alerted root causes of failure, potential data sources for condition monitoring can be defined.

SUBJECT MATTER EXPERTS (SME’s) are aware of the equipment that could be monitored for CBM and can determine how to use available information to assess asset condition. They are also key in getting instrumentation to help with condition monitoring.

MAINTENANCE PLANNERS are usually involved in designing 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 & VENDOR MANUALS are a great resource to find vendor maintenance recommendations and where condition-based requirements are defined. Industry references illustrate incidents from many similar plants in your industry and where CBM needs to be applied or where it's being applied well. They also help with putting together the condition parameters and any necessary combinatorial parameters that are necessary.

Once suitable candidates to pilot CBM have been identified, it is important to discover and refine information that will guide CBM.

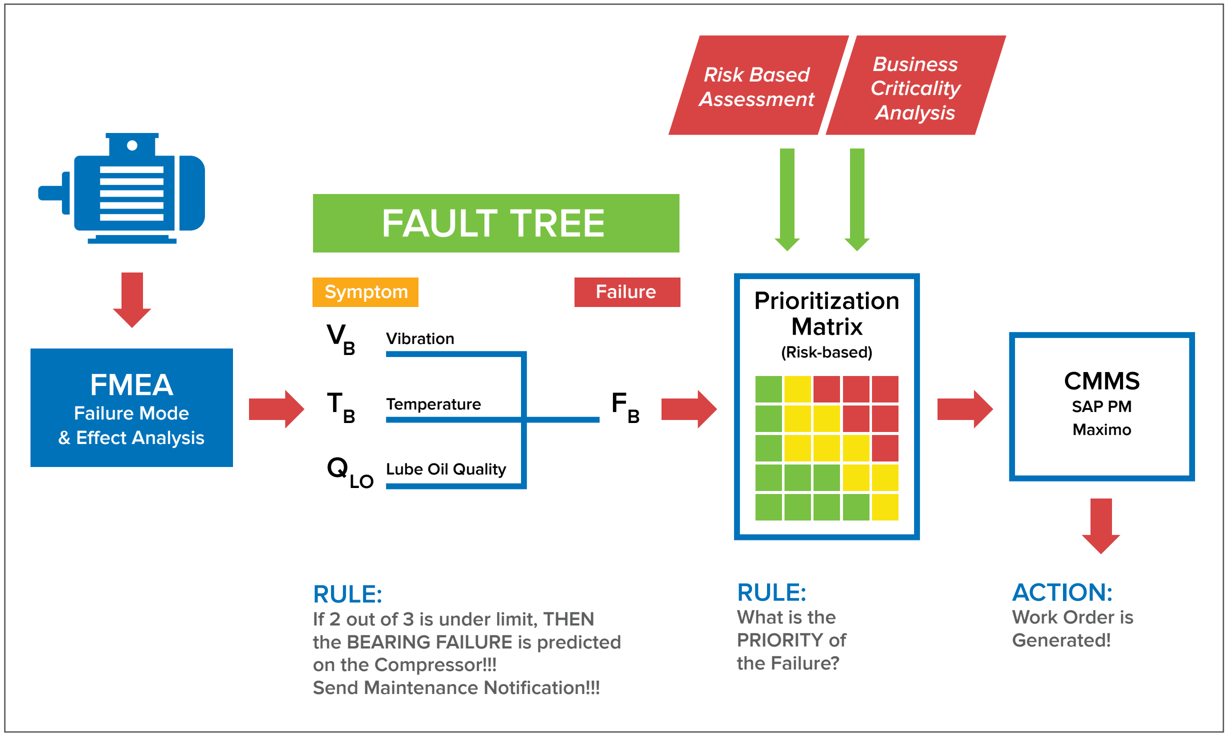


Figure 5: Prioritizing asset candidates and conditions to monitor

4.2 Condition Monitoring

Condition monitoring is the process of using asset data to monitor a parameter (vibration, temperature etc.) in order 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 meter updates to a CMMS when CBM is fully implemented.

Condition monitoring could be as simple as recording operator rounds (by shift, weekly, monthly, etc.) or collecting hour-meter readings or as complex as running Fast Fourier Transforms (FFT) on current and voltage waveforms of transformer windings and analyzing harmonics. Condition monitoring results could be a state value (indication of an issue) or an analogue value. The analogue value could be monitored separately and used in many ways, including updates to CMMS.

Often, but not always, condition monitoring involves specialized equipment that looks at a certain aspect of an asset to understand an aspect of its condition such as vibration, acoustic monitoring, motor current signature analysis, etc. Whether or not specialized equipment is involved, the results or indication of the condition are only available using dashboards, displays and/or reports, as opposed to being integrated with a related asset in CMMS. In some cases, notifications alert individuals of certain conditions, but this is still only condition monitoring and not CBM. Condition monitoring should not be confused with predictive maintenance or the result of a single diagnostic test executed by a human.

Bottom line, condition monitoring is a prelude to CBM. We recommend starting with condition monitoring alone to test the ideas, concepts, etc. behind CBM rules before integrating them with a CMMS.

Sometimes, condition monitoring involves existing process variables and typically aggregates them to determine an asset's health, relative to others and is called "condition assessment."

4.3 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 being an overall condition indicator in a range or state that can be compared to other assets. 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, fleet, etc. wide comparisons. CA helps prioritize capital replacement/improvement dollars, system engineering time or maintenance prioritization, etc.

Condition assessment often makes use of data other than performance data including maintenance process data such as Mean Time Between Failures (MTBF), Mean Time To Repair (MTTR), asset criticality, CM/PM ratios, recent trends of damage and cause codes, etc. It may also include nameplate and other static data such as age, manufacturer, grade, etc. These factors are often valuable as recent values and historical trends.

To develop a CA indicator, factors have to be developed for the equipment peer group using available data where CA is a sum of the individual factors:

$CA = F1*M1 + F2*M2 + F3*M3 + F4*M4 + F5*M5\ldots$; 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, a case statement should be developed that compares the actual condition indicator to a set of values and determines a result of a number between 0 and 10. A default or typical value should be provided for missing data.

With this method, the result should be a number between 0 and 10. The CA algorithm should be peer group specific and applied periodically to each asset within the peer group and the result (CA and each factor) historized to provide the ability to associate and asset with its CA and trend these values. The CA value can be used with CBM by qualitative assessment. For example 0-2 creates a maintenance order based on maintenance plan x.

These results also provide a current and historical value for the condition of the asset that is useful in capital replacement determination, work prioritization, system health assessments, etc.

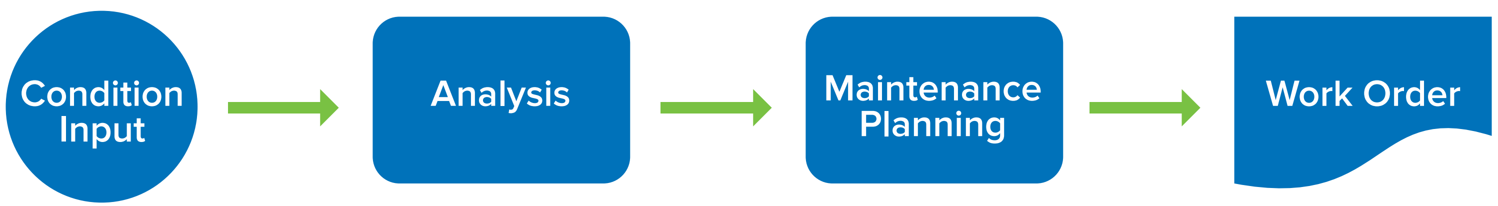
4.4 CBM Configuration

CBM configuration is primarily done within the CMMS where the maintenance processes (plans) are configured. For CBM, maintenance processes are configured through asset conditions and use a meter (or measurement point) where a condition is recorded. Remember, CMMS that support CBM use a meter that triggers 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 (it's like changing your car's oil every 7,500 miles or 12 months, whichever comes first).

The meter's current and previous values are used by the CMMS preventive maintenance program to predict when the 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 can result in a reluctance for maintenance to take seriously these orders as it overwhelms them with "noise." Systematically removing these "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 based on an asset condition can be even worse. If the asset fails and its criticality and impact to the plant or process are significant.

Following a process that includes optimizing prerequisite steps, like condition monitoring and assessment, ensure that condition indicators that update CMMS meters support reliable maintenance order predictions.



4.5 Quantitative-based meters (count)

Meters are defined in one of two ways, either quantitative (aka usage or counter-based) or qualitative (aka 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, start/stop cycles, etc. To use a recent airline example, the compression and decompression cycles of certain 737 jets has been limited to 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, i.e. they have the greatest impact in determining when a maintenance order will be produced by the CMMS maintenance process job.

Special Considerations:

1. Since meters generally run from 0 (or their previous value) to current value, there should be consideration for resetting the start value within the CMMS for the next scheduled maintenance once maintenance is complete.
2. 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.
3. 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.

4.6 Qualitative-based meters (state)

Qualitative-based meters consist of two or more discrete state values and are 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 colours. When calculated data indicate that there is a defined state change, a meter update is sent to CMMS. The maintenance plan is informed to take specific action in the CMMS based on this 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 that convert this information into four states. These states indicate progressive health conditions. 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 define tasks.

Special Considerations:

1. The timing of an assessment algorithm should be such that it does not run more than once between cycles of the CMMS maintenance process. If it did, 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.

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

As stated, it is not necessary to automate CM for CBM; however, the discipline required to manually input this data into CMMS or other workflow systems can introduce another important failure mode. Many modern systems 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.

Automating the end-to-end process allows groups to refine their knowledge over time and continuously make systematic improvement across the entire operations. Unifying systems that can scale across functional boundaries provide common operating platform and an operational system of record. A system that meets these challenges should have these characteristics:

- Support for Open Standards
- Scalable
- Highly Secure
- Highly Available
- Support for legacy automation and future data source systems
- Positioned to leverage BIG DATA and Business Intelligence tools and techniques

5 CBM and the PI System

The PI System delivers an open infrastructure to connect sensor-based data, operations and people. It empowers companies to leverage high fidelity, real time data to support operational intelligence and strategic business initiatives.

As stated in the introduction, 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
- Capturing and storing 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 values.
- Powerful means to surface asset health information. Information can be consumed in a wide variety of ways by users as well as other enterprise systems.

5.1 A PI System Ecosystem Overview for Condition Monitoring

1. Asset data have disparate sources and exist in a variety of systems. Source data need to be integrated and evaluated to identify parameters that accurately reflect asset health and appropriate maintenance activities (e.g. run time, operations/cycles, etc.) (Figure 6).

2. OSIsoft has developed over 450 interfaces to collect data time series data from real time systems. PI Interfaces support buffering and redundancy to ensure no data loss. Data are stored in the PI Data Archive for simple retrieval and analysis. A unique method for storing incoming data streams minimizes resource needs (network bandwidth, processing cycles, disk space, etc.) while maintaining the fidelity of the original instrument or process.

3. The PI Asset Framework (AF) is a customizable, sophisticated asset modelling system that organizes data streams (e.g. assets, devices, systems, etc.) to reflect asset topologies and related function. Assets are represented as elements within PI AF to support rollups. Topological representation can include static data, access to streamed data, calculations to assist in condition determination, data from external systems (e.g. nameplate, CM/PM ratio, etc.)

4. Analytics automatically perform complex calculations on both incoming data streams and archived data. Analytics within AF keep context across raw data source, relationships to other streams and external data sources (e.g. relational, external systems, etc.) to produce meaningful information (Figure 7). Users deploy PI System Analytics to identify asset conditions such as high vibration, low pump efficiency, etc. or calculate an aggregation of run time, material processed, etc. or combine a number of individual condition factors into an asset health score. Events PI Event Frames create a bookmarking function to easily link process data to pertinent events or identified timeframes (Figure 8). Analytics and Event functions are synergistic in a CBM

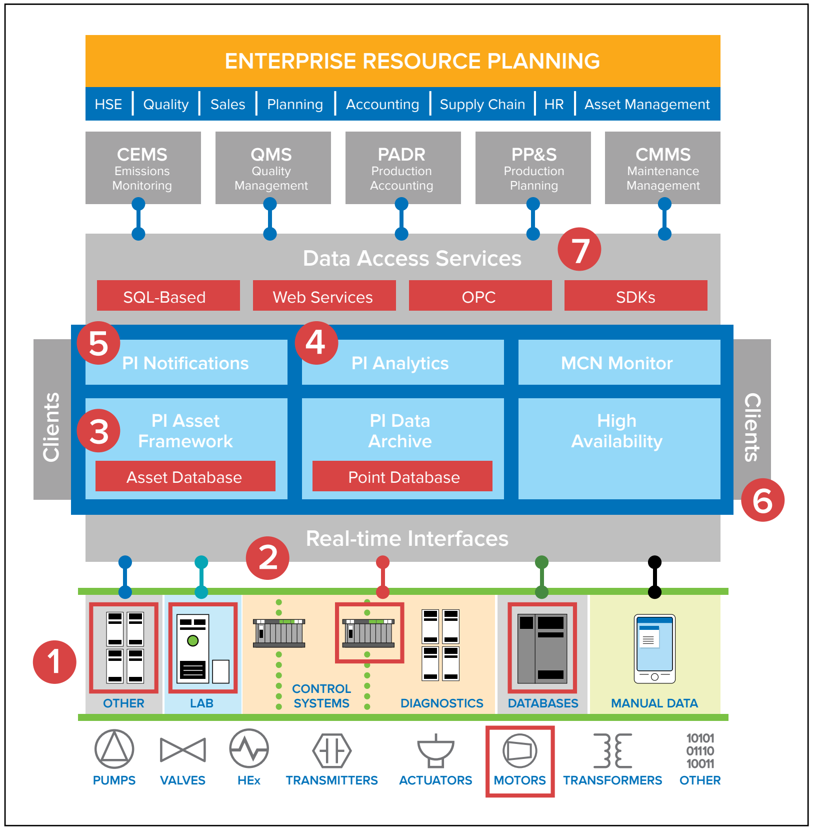


Figure 6: This figure shows the PI System integrated with data sources and enterprise systems as applied to condition monitoring and CBM. The steps enumerated by the red dots show a sequential flow through the ecosystem and are described in the main text.

context. Asset analytics can define reference events based on process data. Event bookmarking allows users to see data that occurred before the actual trigger. For example, when a unit or piece of equipment trips, Event Frames easily frame data for a time period around the trip so users can analyze its root cause. Repeated CBM events can be layered to gain insight about how the assets have operated over long periods of times by comparing them to each other. Event frames also provide placeholders for additional data to be added later. For example, an engineer could add cause code values or programmatically add data returned from the CMMS, such as the Work Order (WO) number.

5. PI Notifications When condition indicators or predefined limits are out of range, PI Notifications alert defined individuals or update another enterprise system based on analysis results and events. 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 9).

6. PI Clients and PI Data Access Client tools provide information to a wide variety of users and address the needs of stakeholders in a broad organization. Client tools can surface event and other analytical data. This information is useful not only for ascertaining specific asset conditions but also in evaluating asset conditions over time through root cause analyses and trends relative to asset nameplate and process data.

7. Finally, the PI System can integrate asset data to a wide variety of other systems and IT platforms through industry standard technologies such as Web Services, OData, OLEDB, JDBC, SDKs, etc. These methods help integrate time series information (data from real time systems) with other enterprise platforms such as CMMS, ERP/EAM, reporting tools (BI), desktop

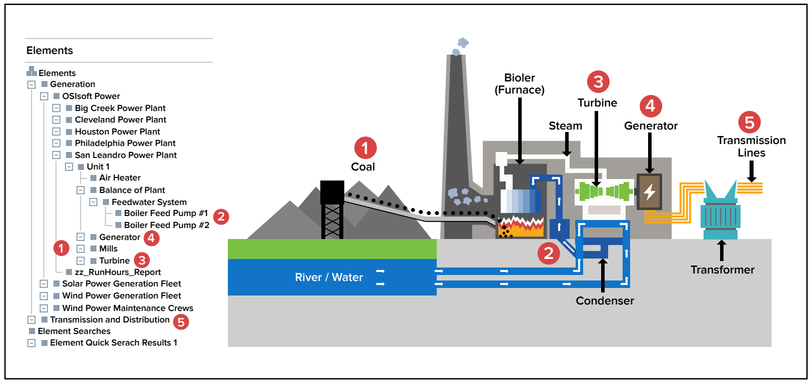


Figure 7: The PI Asset Framework (AF) captures asset, plant and resource topology. Organizing data through PI AF makes data accessible to users across sites and keeps data streams in functional context. Asset- and element-relative calculations can be performed to standardize visualisation across sites. Yellow circles represent assets organized as elements in the AF template.

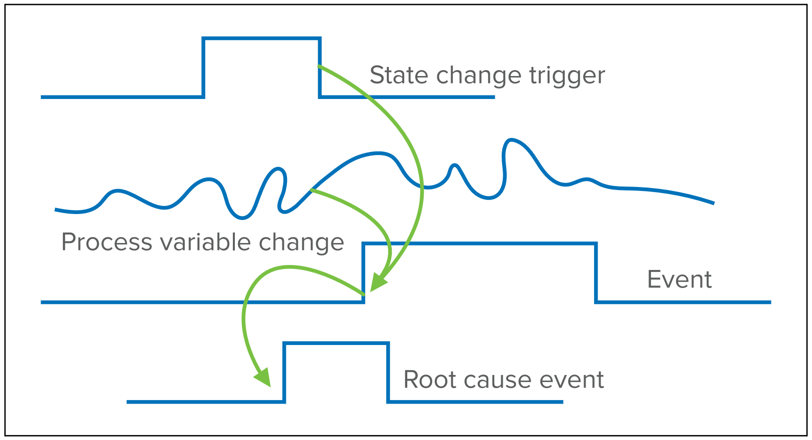


Figure 8: An Event Frame is initiated by a trigger that could be a state change in process data. Process variable exceptions, such as a rate of change, cross of a limit, operation over a number of times within a time period, can also initiate an Event Frames.

productivity and custom applications. Push mechanisms send data to people and systems using any number of delivery channels, for example by sending emails or invoking a web service. The Pull model is enabled by PI Data Access technologies using any number of technologies, including popular open standards methods such as OData.

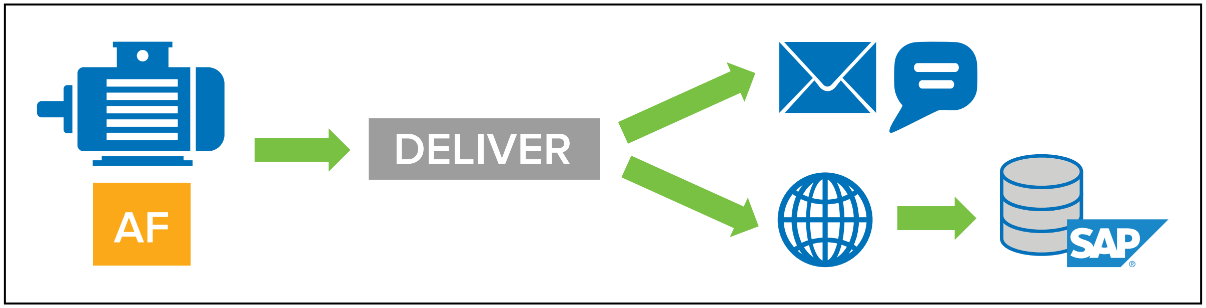


Figure 9: PI Notification alerting people and systems to events happening in process data

6 PI System integration with ERP/EAM

The following high-level concepts will be considered for integration:

1. PI System as a real time bus, accessed via the CMMS directly (pull).
2. PI System as a real time bus, using middleware (e.g. EAI broker) for integration scenarios
3. with CMMS (push/pull)
4. PI ACE, as a programming environment, invoking services of the CMMS for integration
5. (push)
6. 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 (e.g. JMS queue), which would make this a "push" interface.

It's important to realize that often the deciding factor in determining integration with CMMS applications for CBM purposes comes down to organizational preferences. There are many organizations that have standards for middleware, for integration to EAM/ERP, for preferences of configuration over coding, etc. These preferences, skill sets, costs, etc. can factor more into the decision than the technical approach.

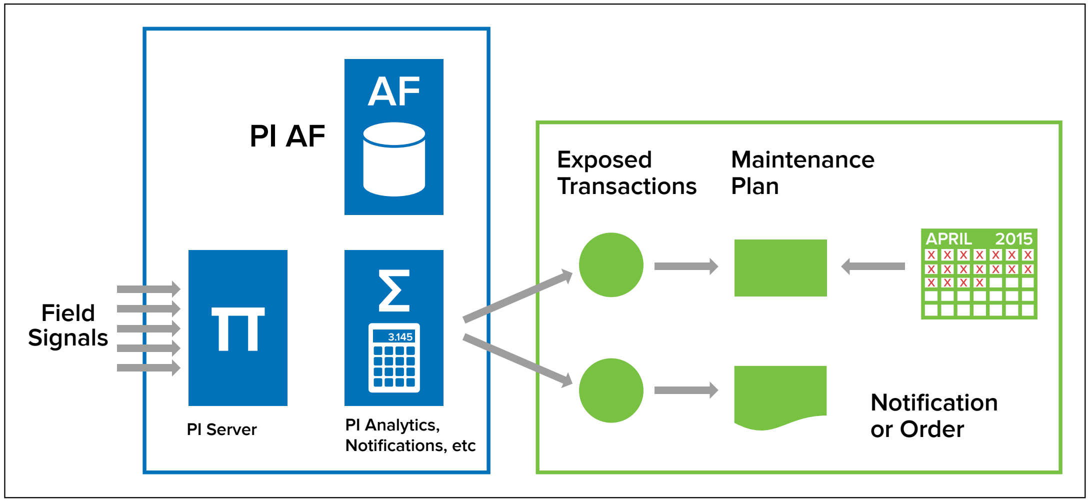


Figure 10: Conceptual approach to integration of real time data with CMMS

6.1 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 (in this case the CMMS program) install for the PI SDK or PI ODBC/JDBC or PI OLEDB. The CMMS may also invoke remote web services to read/ write PI System data or use our evolving PI System Access components such as the Web API or OData (Figure 11).

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 and reset counters in the PI System or Event Frames that indicate work is needed in order to initiate the next event frame.

This is a very simplistic approach 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 in older implementations, PI ACE. The following table lists some pros and cons of this approach:

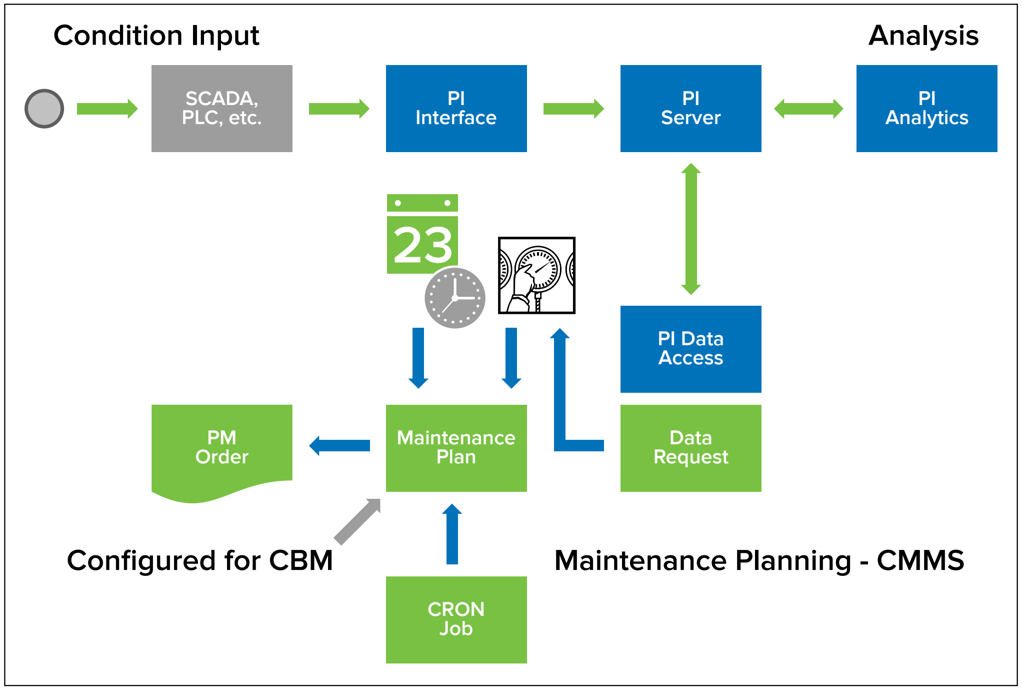


Figure 11: PI as a Real Time Bus accessed by CMMS directly

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

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

This method is similar to the above only 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 actually be a part of the CMMS stack (for example, with more advanced EAM/ERP applications).

With middleware, the interaction with the PI System could be scheduled (pick up a summary of data daily) or 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 (Figure 12).

Also, the PI System could 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 indicator 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, via PI ACE) or open (via web services) depending on the middleware technology employed.

An example of an integration scenario initiated by an event in CMMS could include an asset change (location, equipment and 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.

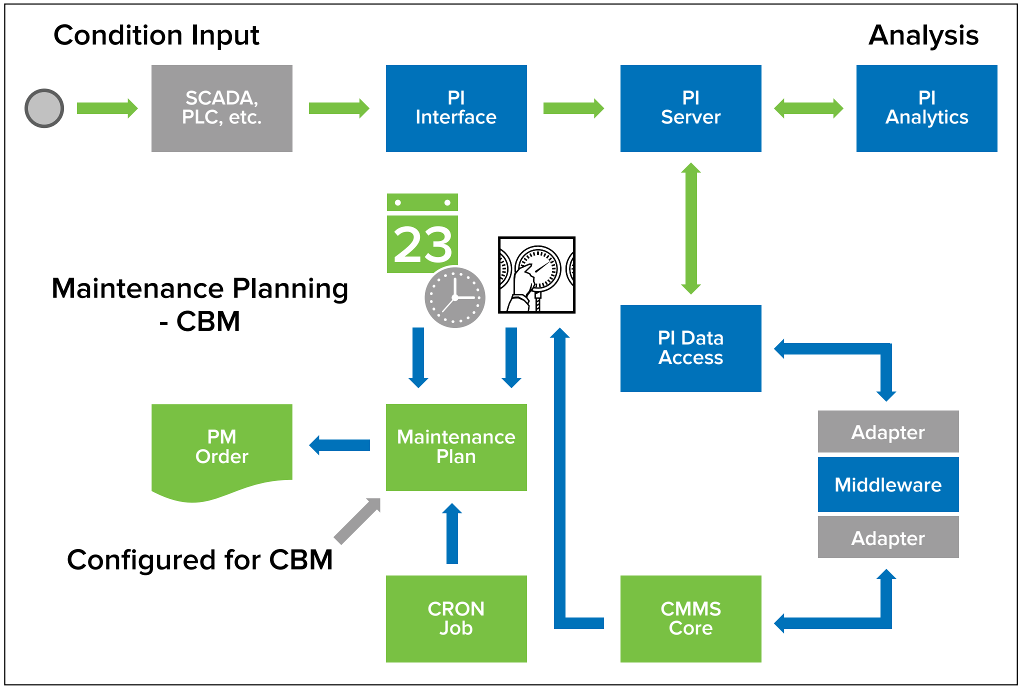


Figure 12: Integrating PI with CMMS via Middleware. The figure above shows a simplistic diagram of the integration of the PI System with CMMS via a middleware component.

Some examples of common middleware components include:

- IBM Websphere MQ Series – is IBM's offering for enterprise integration and is a java environment. A typical way this is used is to invoke web services or add entries 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 – is SAP's primary EAI broker (formerly XI) and integrates very easily into SAP business processes although it is not limited to SAP integration (although rarely used outside an SAP enterprise).
- SAP's MII - 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 – standards based	Requires a PI System specific adapter that supports specific functions
Standards based, when middleware is used for a number of integration scenarios	Limited functions as this is based on specific functions

6.3 PI Analytics (or similar) invoking services of the CMMS for integration (push)

In this scenario, PI Analytics (or similar) operates based on PI System events or clock schedules and invokes the integration process with the CMMS. The integration method could vary depending on the enterprise and technology preferences. It could be a custom program, a custom data reference or some simple MS PowerShell scripts. Many integrations could include:

- Invoking a web service
- Updating a database using an OLEDB provider (or update a queue, e.g. JMS queue)
- Invoking an update to CMMS via a middleware adapter
- Programmatically invoking an update to CMMS, e.g. using an SDK or other method, for
- example calling an SAP RFC.

Figure 13 illustrates a small part of custom code (PI Analytics) that invokes the integration into a 3rd party system. This may be a custom data reference, MS PowerShell script or something similar.

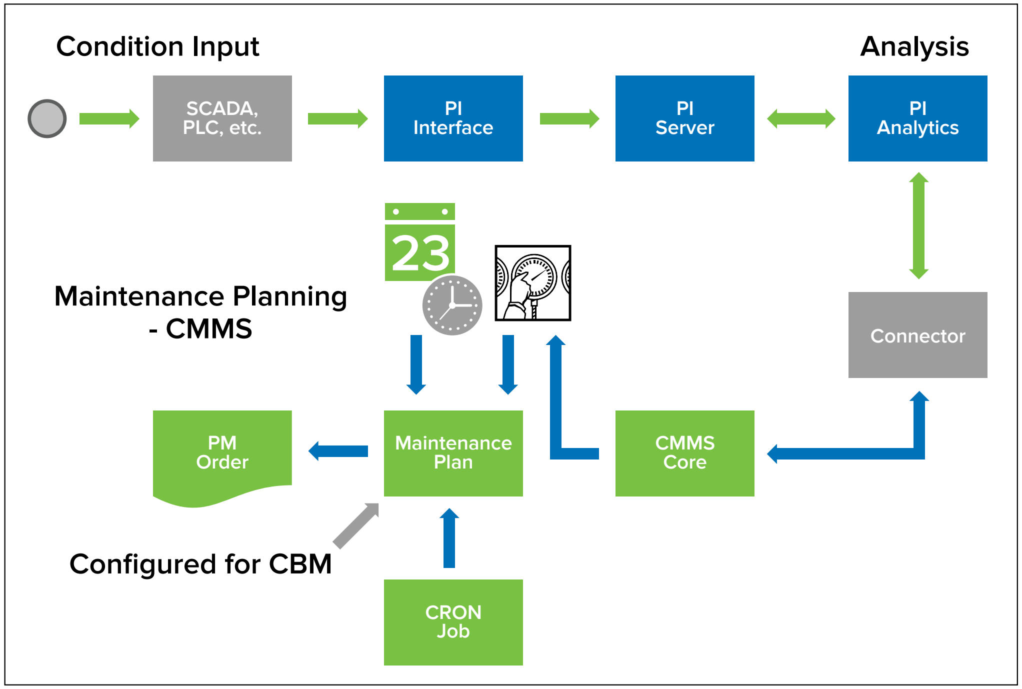


Figure 13: PI System Integration with PI Analytics

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

PI Analytics (or similar) as an on-demand integration method (push)	
PROS	CONS
Approach suitable to minimal PI System component installations	Requires some customization of the coding for the integration. 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	

7 CBM Solution Examples

7.1.1 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 (e.g. dial- up, dedicated systems). Online monitoring presents 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 more 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, top oil tank temperatures, etc. 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 14 represents a simplified fault tree for large power transformers. There are typically a number of specific condition indicators monitored on these devices. The most common ones include load values, temperature sensors and dissolved gas analysis (DGA) monitors.

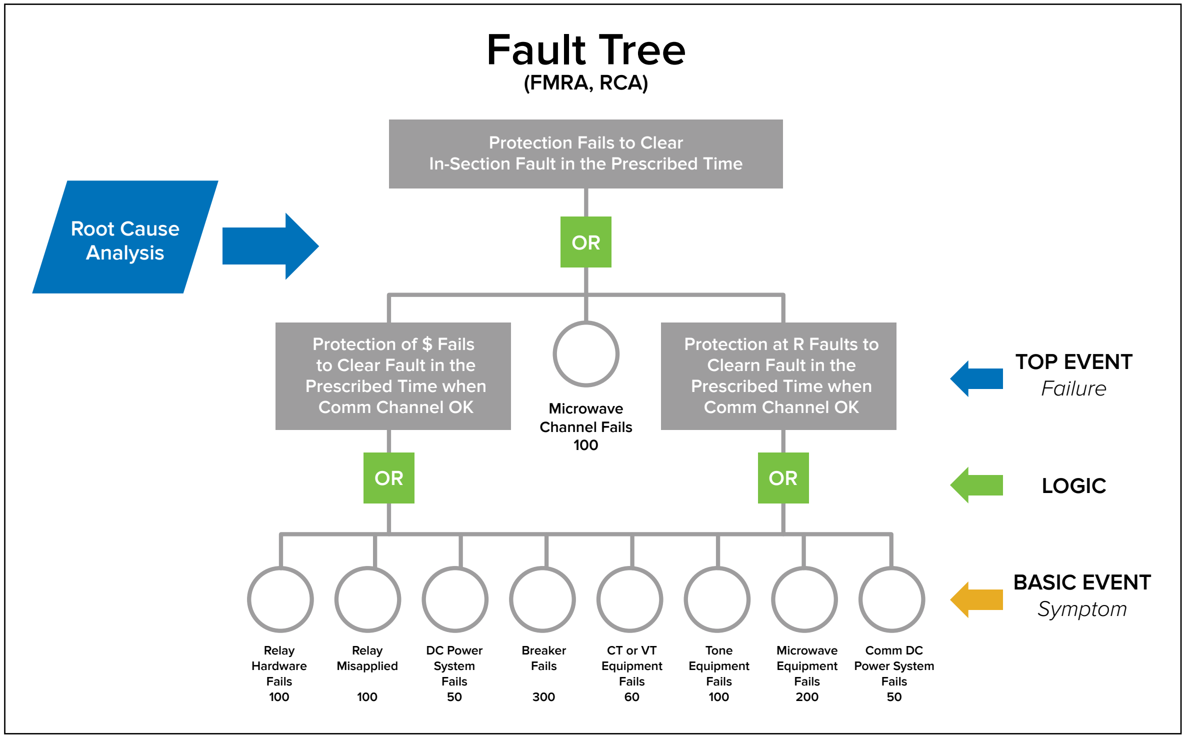


Figure 14: Example fault tree for large transformers

7.1.1.1 Transformer Monitoring and Analysis

Online transformer oil analysis monitors 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) is in need of maintenance or further diagnostics. Manufacturers provide guidelines for refurbishment or replacement for transformer oil impurities. Some transformers have gas detector or Buchholtz relay (usually on conservator models) or pressure relays, which detect either sudden rise or high 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 and stored as an asset attribute which can be used to initiate action before a breaker relay trip event.

7.1.1.2 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 that the transformer be taken out of service and isolated from the surrounding circuits. This is simply not practical for most 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 meters called phasor measurement units (PMUs) transformer health can be calculated online in real time based on two fundamental measurements:

- Sweeping Frequency Response Analysis. This measurement is based on the delta between a Fast Fourier Transform 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. The high resolution voltage and current information provided by the PMUs is used 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 of these analyses are good 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 that a problem 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 visualisation clients in real-time. It also stores both input and calculated data in the PI server archives.
3. The OSIsoft FFT 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 Analysis Engine (or custom programs using the PI 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 other methods 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 the Excel environment for complex analysis and presentations
8. PI Notifications and AF 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.

7.1.2 Transformer References

- TVA - DobleARMS and PI System Bring Standards-Based HV Asset Management to TVA
- Hydro Quebec - AMI Analytics & Power Transformer Simulation Laboratory for Proactive Maintenance II
- FinGrid - Building a Condition Monitoring System Based on PI AF

Back to Table of Contents

7.2 Compressors

7.2.1 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. It is used by operations in virtually every industrial segment from aircraft and automobiles to dairies, fish farming, and textiles.

Often, plants often 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.

7.2.2 Compressor Monitoring and Analysis

Figure 15 provides a basic overview of sources of data relevant to compressor health and monitoring.

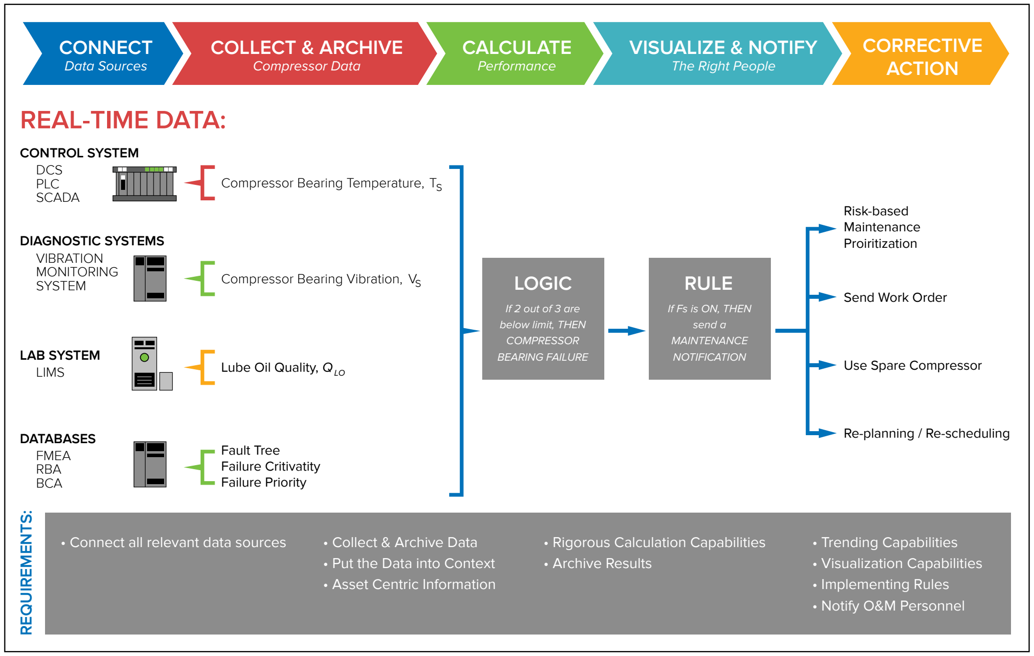


Figure 15: Compressor Data & Maintenance Condition Monitoring

7.2.3 Compressor Actionable Output

In the example shown in Figure 16, a report was sent to the Maintenance Department for review of the data for their recommendation. This may happen as a function of a business process or in conjunction with other notifications such as CMMS or CRM.

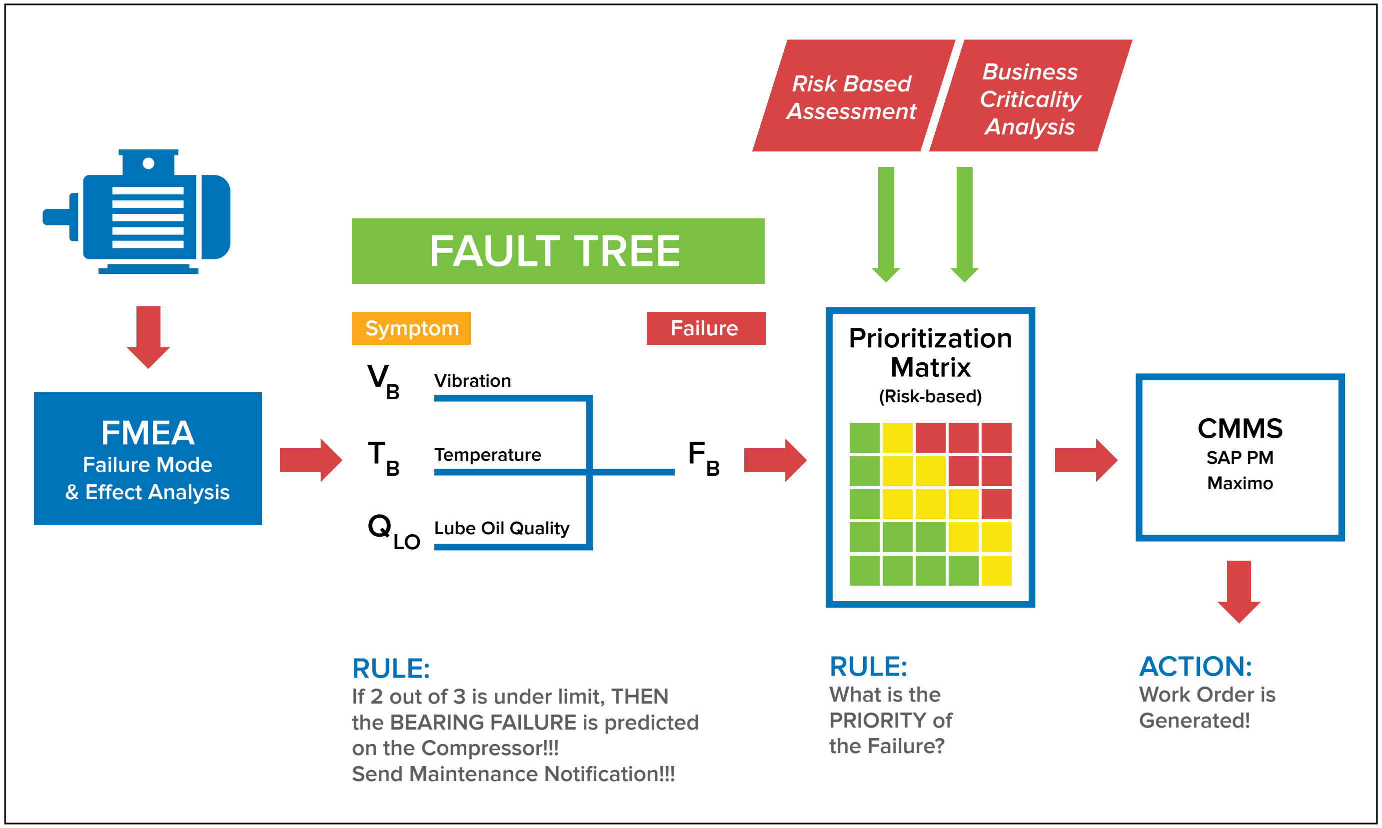


Figure 16: Example Process Overview for Compressor Asset Health

7.2.4 Compressor References

- Alyeska Pipeline - Achieving Reliability-Centered Maintenance and Diagnostics with the PI System
- 2012 – Retrofitting Compression Equipment and Interfacing Systems for CBM
- Improving Reliability with Caterpillar Condition Monitoring Services
- 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. http://www.compressedairchallenge.org.

8 References

- Achieving Reliability Centered Maintenance and Diagnostics with the PI System – Alyeska Pipeline
- Sempra Energy (SDG&E) - PI System for Enterprise Information Decision Support
- PSE&G - CMMS Foundation for Smart Grid Modernization or Case study 2005
- Arkema Case Study 2005
- Alyeska Pipeline - Achieving Reliability-Centered Maintenance and Diagnostics with the PI System
- KEPCo - Development of Real -Time Damage Monitoring System for the Optimization of Inspection Planning of Power Boiler Tubes
- Using PI to Back -Test Usage and Condition Based Maintenance Strategies to Predict QuantiableBenefits Prior to Deployment in Asset Management – DTE 2009
- 2012 – Retro tting Compression Equipment and Interfacing Systems for CBM
- Improving Reliability with Caterpillar Condition Monitoring Services
- How PI Played a Key Role in Helping Dofasco Achieve Maximum Asset Reliability
- Making the Most of Your Assets, Dow Corning

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