contents

Optimize Maintenance Resources through Improved Process Diagnostics

Alireza Haji-Valizadeh
Technology Development Manager
ControlSoft, Inc.
Cleveland, OH 44143

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ABSTRACT

Process industries have implemented maintenance productivity tools to minimize impact of equipment failures, to insure maximum process on-stream time, and to minimize unintended interruption to operations. The focus of these tools has been predictive maintenance based on the condition monitoring of individual machine and equipment components over a period of time. Amongst maintenance productivity tools are process monitoring and diagnostic tools which are usually system focused and integrate automation technology with process, measurement, and operations information. Process monitoring detects system problems such as improper interaction of equipment and inappropriate operations outside expected boundaries, and then prompts appropriate action. In this paper we review the basic characteristics that these tools should possess in order to easily connect to existing control systems, handle robust analysis and diagnosis, and also provide reporting in order to be effective maintenance productivity tools.

INTRODUCTION

Keeping production plants running smoothly and efficiently has always been the objective of manufacturing organizations. Today's economy has also forced manufacturing organizations to constantly strive for opportunities to maximize performance and throughput of the production systems. Automated Process Diagnostics and Loop Performance Monitoring (*PDLPM*) tools considerably contribute to achieving these objectives.

In recent years, in order to prevent unwanted interruption to production due to device failures, and in turn to increase overall throughput of production, manufacturing organizations have used

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routine *preventive maintenance* schemes. However, normal preventive maintenance addresses only problems on the device level, and leaves unattended the problems on the loop, supervisory, and information management levels. Furthermore, preventive maintenance is costly effort and thus manufacturers tend to apply it to the most critical production components and use maintenance on demand for the rest of the system [4]. To effectively minimize maintenance costs and the resources used for maintenance we can combine preventive maintenance efforts and process diagnostic and monitoring activities and use a *predictive maintenance* scheme where the maintenance effort is focused mainly on problematic components with the highest priorities. Furthermore, the use of process diagnostic tools can extend the reach of predictive maintenance beyond the device level to cover problems in the loop and supervisory levels of the plant.

An automatic diagnostics and performance monitoring tool also provides utilities for auditing loop performance. Assessment and prioritizing of opportunities to optimize plant operations are crucial steps in improving plant operations. Using an online automated system for identifying opportunities to improve plant efficiency is essential. This is a consequence of having time-varying conditions and improvement priorities that generally depend on production schedule and recipe. A network of PDLPM tools can tie scattered processing locations together, thus giving management the centralized information it needs to identify opportunities for improvement. Application of PDLPM tools for loop auditing minimizes maintenance costs and resources. Reducing the resources needed for performance auditing will free resources to focus on the unexpected events requiring immediate attention.

Front end of any predictive maintenance system is an automated process monitoring and diagnostic activity. In the following sections we review the general characteristics that a PDLPM tool as a predictive maintenance productivity tool should possess.

GENERAL CHARACTERISTICS OF PDLPM TOOLS

For a process diagnostic and loop performance monitoring tool to be an effective predictive maintenance productivity tool it should provide the following services:

1. Data connectivity,
2. Plant-wide integrated loop organization and information access,
3. Process diagnostics,
4. Loop performance assessment,
5. Process report generation,
6. User prompt system,
7. Open architecture and integrated with plant information management systems.

The process of diagnosing a process fault and bringing it up to the attention of maintenance personnel requires most of the above services. What follows is description of each service in more detail.

DATA CONNECTIVITY

Diagnostics requires collection and processing of data. Thus any PDLPM tool should support data connectivity. This means that PDLPM tool must be able to get data from various devices and software. It also means that a PDLPM tool must make its own internal data and information available to other systems.

Diagnostics provided in PDLPM tools could be online and / or offline analysis functions. Online analysis requires access to real time process data, and offline analysis is based on historical process data. Thus a PDLPM tool is a client to both online and offline data. In the other hand, PDLPM tools should provide access to the results of their data analysis in both online and offline fashions. For example, alarms managed by a PDLPM tool should be detected and communicated to the alarm listeners in real time, and they should be logged in alarm logs for offline analysis of the plant condition at the time of alarm. Therefore a PDLPM tool is in general a server for both online and offline data.

Usually PDLPM tools support data connectivity by providing data access via open and standard communication protocols and interfaces like DDE, OPC, HDOPC, ODBC and XML. Data connectivity ensures fast and easy integration of data with other applications and technologies. It also reduces maintenance effort and costs associated with applying PDLPM tools.

PLANT-WIDE INTEGRATED LOOP ORGANIZATION AND INFORMATION ACCESS

In today's manufacturing facilities one can find hundreds and possibly thousands of automatic control loops based on various vendor platforms. It is nearly impossible to monitor the performance of even the most critical control loops without some formalized assessment and monitoring tool. A PDLPM tool should be foremost an effective loop administration tool. To this end a PDLPM tool should provide utilities for defining, classifying, and organizing plant loops, devices and diagnostic functions.

Organizing and grouping of loops and devices could be based on the area of their installation in the plant or based on the functionality provided by the loop. Control loops in a typical plant reside on many different platforms. Therefore, an effective PDLPM should provide an easy and user-friendly way for defining loops, irrespective of the brand or vendor of the loops' platform. To ease user-setups for process diagnostics, if possible, a PDLPM tool should query existing plant loops from underlying DCS or PLC systems, and automatically generate communication tags for the user-selected loops. PDLPM tools should also provide easy on-demand access to the essential information of any loop for maintenance personnel. In addition to organizing loops a PDLPM tool should also provide a logical organization for diagnostic functions that are being executed at any time. This requires modularizing diagnostic functions based on their functionality, or the loop that they are applied to, or both.

Figure 1 depicts a possible organization hierarchy where the levels are plant, area, loop, and diagnostic functions.

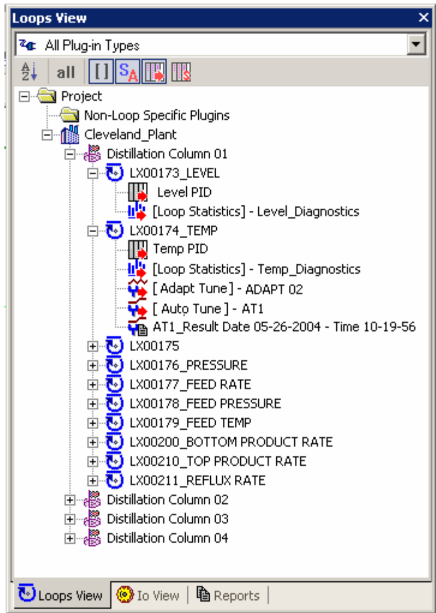

FIG. 1 – LOOP AND DIAGNOSTIC FUNCTION ORGANIZATION

PROCESS DIAGNOSTICS

In this paper, the term "*Process Diagnostics*" refers to software-assisted automatic diagnosis of faults in process operations. Plant economics in today's competitive market requires maintenance personnel to monitor and assess operation of important loops for process diagnostics. Good process diagnostic reduces production system downtime and thus increases profitability of a plant. Diagnosis involves recognizing faults by observing detectable and observable fault symptoms. Techniques used by various PDLPM tools for detecting and observing fault symptoms are vast. For applications in process industry many of diagnostic techniques, at some level of abstraction, belong to the following three categories: 1) Model based diagnostics, 2) Diagnostics based on artificial intelligence (or expert systems), and 3) Diagnostics based on data trend analysis. Many diagnostic techniques could be used in both offline and online fashions if sufficient computational resources are available.

In model based diagnostics the historical data of fault-free process operation is used to develop a reasonably accurate model for the underlying process. The model could be a class of identified parametric dynamical equations or a trained neural network. Then the deviation of a process value from the corresponding calculated model output is considered to be a fault symptom. In artificial intelligence (or expert system) based methods process faults and their associated symptoms are modeled directly. In this case the model could be a database of various fault data patterns, trends and / or clusters. Process condition detection, pattern recognition and data clustering techniques are used in this category. Trend analysis mainly refers to process-conditioned statistical analysis of real-time and historical data. The purpose of analysis is to detect deviation from process norms, to quantify process variability, and to identify the sources of process variability. The simplest and traditional example for this type of diagnostics is alarm management.

There are generally three levels of sophistication in process diagnostic tools. The simplest level – Level 1 diagnostics – is to detect fault or abnormal process conditions and alert maintenance personnel. Level 2 diagnostics requires PDLPM tool to suggest fault remedies to maintenance personnel as well. The highest level – Level 3 diagnostics – is rendered when the PDLPM tool could also automatically take corrective actions in the faulty system.

Traditional PDLPM tools provide Level 1 process diagnostics mainly by alarm generation, alarm management, and sensor validation. An advanced PDLPM tool should provide tools for applying various diagnostic techniques. It should also extend diagnostics to Level 3 at least for PID based loops that constitute about 97% of process industry loops [3]. All critical loops require a regular performance review to determine if controller degradation has occurred, in which case tuning changes are required. When a poorly performing control loop is identified it is necessary to diagnose the cause of under performance. Poor performance could be due to improper tuning, improper control structure, changing process dynamics, or faulty system devices.

In order to make PDLPM software an effective predictive maintenance tool it should be extensible so that one could enhance and configure the tool's functionality to address specific needs. Providing diagnostic services through modular software components, and supporting script languages could provide needed extensibility for PDLPM tool.

TABLE 1: FEW PROCESS DIAGNOSTIC TECHNIQUES & TOOLS

DIAGNOSTICS TOOLS AND TECHNIQUES	**DESCRIPTION**
MODEL BASED	In this method one builds models of the system and then compares real system output against model output to detect abnormal and faulty situations.
ARTIFICIAL INTELLIGENCE EXPERT SYSTEMS	In this method fault manifestation in system is modeled. System output is continuously monitored and compared against fault patterns to detect faulty behavior.
TREND ANALYSIS – PROCESS-CONDITIONED STATISTICAL ANALYSIS ADVANCED STATISTICAL ANALYSIS	In this method data trends are analyzed in real time or offline fashion to detect off norm and fault behavior. Most methods in this category are based on statistical analysis of data. Statistics gather on the system are usually process-conditioned, e.g. percent of time being in manual. Statistical analysis could be also for measuring the level process variability (a sign of faulty controller in many situations) and main contributing factors.
DIAGNOSTICS SCRIPT	Provides tools for configuring diagnostic scripts based on statistical measures or other calculated variables. Allows definition and calculation of new diagnostics and

	performance measures, e.g. loop and plant economical indices.

Figure 2 depicts a Level 3 loop diagnostics service using expert system methods.

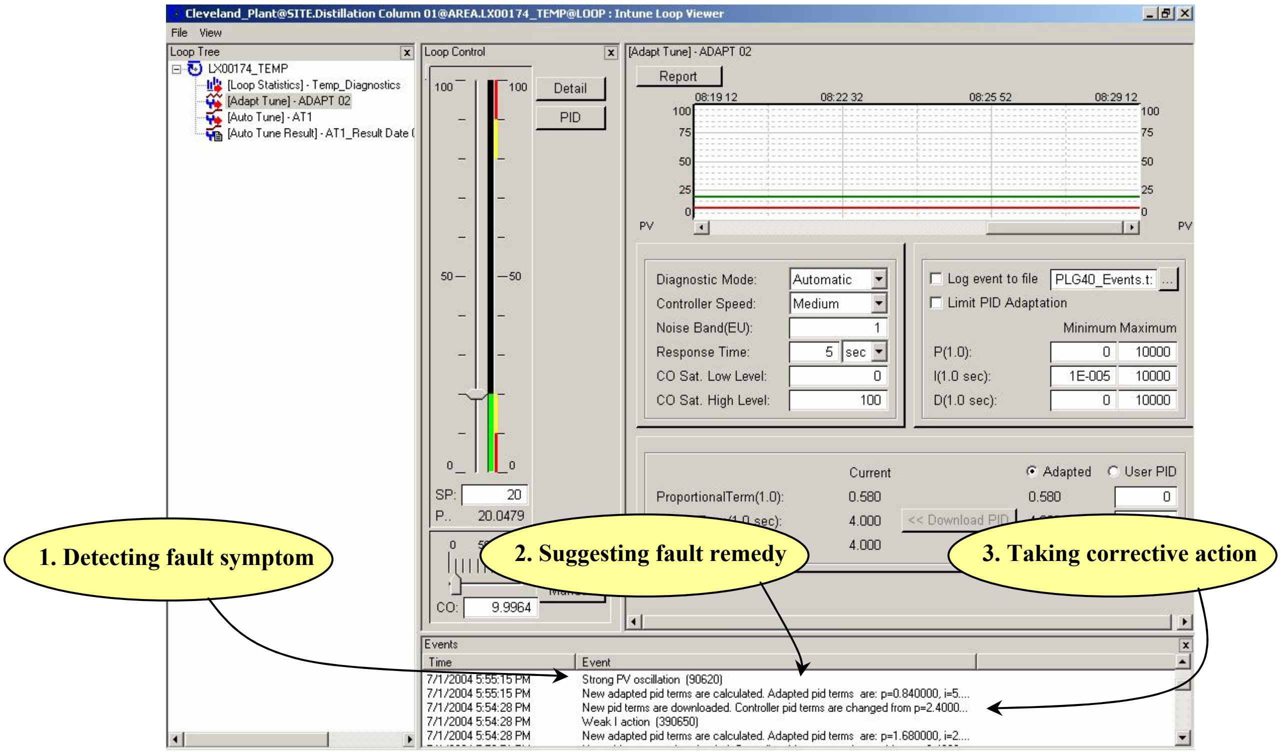

FIG. 2 – LEVEL 3 DIAGNOSTICS OF A PID LOOP RENDERD BY A PDLPM TOOL USING EXPERT SYSTEM TECHNIQUES

In the following sections we focus on process diagnostics and loop performance monitoring using trend analysis method.

LOOP PERFORMANCE ASSESSMENT

Process industry is in need of automated procedures to assess opportunities to optimize plant economics. Where possible, there is a desire to use performance assessment tools in an online-fashion because improvement opportunities change in time and are generally dependent on the production schedule and recipe. One methodical approach to assess process performance is based on the following steps:

1) Development of key process performance indicators,
2) Development of process (and ultimately plant) economical metrics,
3) Relating economical metrics and the key performance indicators,
4) Online calculation of key process indicators and economical measures,
5) Prioritizing improvement opportunities and optimization tasks in order to maximize ROI.

As the level of process automation grows, the feasibility of devising automated performance monitoring and detecting opportunities to maximize also increases.

PDLPM tools should provide various utilities to implement the above five-step performance assessment technique. For step 1 PDLPM tools could provide process-conditioned statistical measures that are indicative of loop performance. Note that many statistical measures could be useful only if calculated conditionally, based on the state of process and instrumentation. For example, consider the average of absolute error, where error is defined as a deviation of process value (PV) from setpoint (SP). This average could be used as an indicator for the performance of loop controller. However, this indicator has meaning only if the process controller is in an automatic mode. Thus, it is essential to condition evaluation of this average to the state of the controller. Another example is PV variability while the loop controller is in manual and the manual value is constant. Then PV variability is a measure of process disturbance. If we consider the same PV variability while the controller is in Auto and SP is constant, then the statistic is a measure of the controller performance. In general calculation of many statistics should be conditioned. If the condition fails then the statistical measure is not updated and data samples are ignored. The condition could be one of the following categories: 0) None – No condition, 1) Auto mode, 2) Manual mode, 3) User defined.

The performance of a process control loop is often measured against some kind of benchmark [1, 2]. Monitoring key performance indicators online and comparing them against their predetermined baselines is one mean for detecting potential problems and determining a need for maintenance, or existence of an opportunity to improve. Establishing baselines is a necessary step for this. Usually, baselines are obtained by some theoretical analysis or by calculating the statistics using historical data that manifest some desired behavior. The process of baseline establishment requires some user interaction. To establish a baseline for online performance indicators, a process of "Bench Marking" is used. Bench marking allows users to retrieve data from OPC historians and then evaluate a corresponding statistical measure for that data. The result is considered to be the baseline for the corresponding performance indicator. PDLPM tools should bench marking. Predictive maintenance is enhanced if a process fault is actively brought to the maintenance personnel attention. To this end PDLPM tools should allow users to specify "Threshold" and "Threshold Violation Scheme (Criteria)" for each process performance indicator. When a performance indicator violates a threshold based on the defined violation criteria then the PDLPM tool should automatically prompt users using email or telephony message. By specifying these features, the user could detect configurable conditions on a statistical measure, and hence, change the system operations based on the detected conditions. The PDLPM tool should also record the most recent times that the threshold violation has observed for a performance indicator for the purpose of tracking process faults.

Steps 2 and 3 of the above performance assessment technique could be implemented by using diagnostics scripts, where the user could develop economical metrics by defining mathematical and logical statements over the set of already defined performance indicators. Using diagnostics scripts, the user could also develop new performance indicators composed of already defined ones.

Step 4 of the above performance assessment technique requires online calculation of performance indicators and economical measures. A PDLPM tool should support two methods of online calculation of performance indictors and economical measures: 1) Calculation based on a moving time window, called Analysis Time (AT), and 2) Calculation based on an expanding time horizon. The first type of online calculation evaluates process situation in the past analysis time, whereas, the second one evaluates performance since a specific time in past.

Step 6 of the above assessment technique is to prioritize improvement opportunities. This requires that the PDLPM tool be able to compare performance indictors of multiple loops with each other, and perhaps, to order corresponding reports based on performance indictors or user-defined economical measures.

In the following table, a set of process performance indictors of interest is listed. Reference [2] also lists a few other indicators of interest.

TABLE 2 – A SET OF PROCESS PERFORMANCE INDICTORS

NAME Title of Performance Indicator	**DESCRIPTION** Description of Performance Indicator	**UNIT**	**TYPE OF CALCULATION** **DEFAULT CONDITION** **SUPPORTED CONDITIONS** **ONLINE / OFFLINE STATUS**
Error Distribution	Frequency distribution of Error samples during Analysis Time.	N/A	Apply Moving Window Condition 1 Conditions 0,1,2,3 Online
High (Low) Alarm Time Total	The percentage of the past analysis time that the process value has been above (below) the high (low) alarm level.	% of AT	Apply Moving Window Condition 1 Conditions 0,1,2,3 Online
High (Low) Alarm Time Current	The length of the time that the process value has been continuously above (below) the high (low) alarm level.	Sec	N/A Condition 1 Conditions 0,1,2,3 Online
Controller Output High (Low) Saturation Total	The percentage of the past analysis time that the controller output has been above (below) the output high (low) alarm level.	% of AT	Apply Moving Window Condition 1 Conditions 0,1,2,3 Online
Controller Output High (Low) Saturation Current	The length of the time that the controller output has been continuously above (below) the output high (low) alarm level.	Sec	N/A Condition 1 Conditions 0,1,2,3 Online
Mean CO	Mean value of Controller Output that is observed in the past analysis time.	EU	Apply Moving Window Condition 0 Conditions 0,1,2,3

			Online
Mean PV	Mean value of Process Value that is observed in the past analysis time.	EU	Apply Moving Window Condition 0 Conditions 0,1,2,3 Online
Minimum (Maximum) PV	Minimum (Maximum) Process Value that is observed in the past analysis time. The time of the occurrence of minimum (maximum) PV is also recorded.	EU	Apply Moving Window Condition 0 Conditions 0,1,2,3 Online
Current Rate of Change of PV	Current slop (rate of change) of PV.	EU / Sec	Apply Moving Window Condition 0 Conditions 0,1,2,3 Online
Minimum (Maximum) Rate of Change of PV	Minimum (Maximum) of current rate of PV change. The time of the occurrence of Minimum Rate (Maximum Rate) is also recorded.	EU / Sec	*Synchronized with those of Current Rate of PV* Apply Moving Window Condition 0 Conditions 0,1,2,3 Online
Deviation |SP-PV| Current Time	The length of time that |SP - PV| has been greater than Threshold continuously.	Sec	N/A Condition 1 Conditions 0,1,2,3 Online
Deviation |SP-PV| Total Time	The percentage of past analysis time that the value of |SP - PV| has been greater than threshold.	% of AT	Apply Moving Window Condition 1 Conditions 0,1,2,3 Online
Maximum Deviation |SP-PV|	Maximum of |SP – PV| during the past analysis time. The time of the occurrence of Maximum Deviation is also recorded.	EU	Apply Moving Window Condition 1 Conditions 0,1,2,3 Online
Noise Band	Process noise band always is evaluated in manual mode after passing PV through a high pass filter. Noise band is evaluated for the analysis window. After any CO change beyond 1% and at entering manual modes first 60 samples are ignored.	EU	Apply Moving Window Condition 2 Conditions 2, 3&2 Online
Average of Error	Mean value of SP – PV that is observed in the past analysis time.	EU	Apply Moving Window Condition 1 Conditions 0,1,2,3

			Online
Average of Absolute Error	Mean value of |SP – PV| that is observed in the past analysis time.	EU	Apply Moving Window Condition 1 Conditions 0,1,2,3 Online
Average of Square Error	Mean value of square of (SP – PV) that is observed in the past analysis time.	EU Squared	Apply Moving Window Condition 1 Conditions 0,1,2,3 Online
Standard Deviation of Error	Standard deviation of error samples during the past analysis time.	EU	Apply Moving Window Condition 1 Conditions 0,1,2,3 Online
Process Variability	Process variability defined as percentage of average error, i.e. (2 * Standard Deviation of Error * 100 / Absolute Average Error), during the past analysis time.	% of Absolute Average Error	Apply Moving Window Condition 1 Conditions 0,1,2,3 Online
Disturbance	Disturbance evaluated as the standard deviation of Process Value while in manual. The analysis is windowed over the past analysis time. After any CO change beyond 1% and at entering manual modes first 60 samples are ignored.	EU	Apply Moving Window Condition 2 Conditions 2, 3&2 Online
Optimal Loop Quality Index	Ratio of the actual measured error variance to the ideal error variance of a minimum variance controller during the past analysis time.	N/A	Apply Moving Window Condition 1 Conditions 0,1,2,3 Online
Controller Manual (Auto / Track / Other) Mode Time Total	The percentage of the past analysis time that the controller has been in manual (auto / track / or other) modes.	% of AT	Apply Moving Window Condition 0 Conditions 0,3 Online

PROCESS REPORT GENERATION

PDLPM tools need to have reporting capabilities that are oriented toward enhancing predictive maintenance activities. Generally, three aspects of the reporting system could contribute to the effectiveness of PDLPM tools as the following: 1) Report types, 2) Report formats, and 3) Report generation scheme. Report types identify the set of information that is made available to users. For a PDLPM tool this set should include, at least, diagnostics information and key performance indicators. A well formatted report could enhance predictive maintenance. The format of reports not only addresses the quality of presentation, but also provides a level of data processing. A well laid-out diagnostics report could help maintenance personnel focus on the most important data items. For example, laying out performance indictors of many loops next to each other, and ordering columns based on a particular indicator or economical measure could help prioritize maintenance activities. The format of reports also helps the accessibility of the reports. For example reports that are in HTML format could be easily added to database web-based information retrieval system. This greatly enhances the efficiency and maintainability of the process by providing plant wide access to the reports using web browsers. The report generation scheme refers to the time of report generation. Usually three types of report generation are required for a maintenance productivity tool: 1) Regular periodic report generation. This type of generation is more suited to help regular plant performance review in order to determine loop degradation and also process optimization opportunities. 2) Event based reporting where report could be generated if an event, e.g. a failure, occurs in the process. 3) On demand reporting. A PDLPM tool should be able to generate report on demand by maintenance personnel.

USER PROMPT SYSTEM

An online PDLPM tool should be able to prompt users, in occasion, of critical system faults. Prompting could be in the form of a dispatch of an email or telephony message, or based on the traditional alarm generation. In a PDLPM tool the user should be able to configure the dispatch of an email or telephony message when a particular event happens. An event example could be a violation of a threshold for a loop performance indicator that is evaluated in diagnostics engine. An event also could be the satisfaction of a condition on a variable read in by IO subsystem.

OPEN ARCHITECTURE AND INTEGARTED WITH PLANT INFORMATION MANAGEMENT SYSTEMS

A PDLPM tool should have an open architecture where new diagnostics algorithms and / or key performance, and economical indicators could be added to the system in time. The open architecture should also support extending functionality over the space of devices and controllers that the PDLPM tool could work with.

PDLPM information and reports should be readily available through web-access and could be seamlessly integrated with an enterprise asset and maintenance management system. This, in turn, provides a basis for efficient work order issuance for maintenance personnel, and increase productivity of predictive maintenance effort.

CONCLUSION

Process Diagnostics and Loop Performance Monitoring (PDLPM) software could increase the productivity of maintenance activities in the chemical and food industries, if they possess good capabilities of data connectivity, loop organization and information access, process diagnostics, loop performance assessment, reporting and user prompting. They must also have an open architecture and be easily integrated with other information management systems. Advanced PDLPM tools could take a major step in reducing the effort to maintain the process facility at optimal operation. Used in conjunction with equipment predictive maintenance, they could significantly reduce plant maintenance costs.

Application of PDLPM tools provide different benefits based on the timing of the application: 1) initial application identifies existing equipment or control problems, and 2) on-line application identifies poor or degraded performance that could be easily reported through a variety of means, depending on priority and risk. Initial use of the process diagnostics software exposes performance issues such as bad control loop tuning, improper installations, physical constraints, or poor process design. For on-line monitoring, key performance indictors could be explored to assist process control engineers and maintenance supervisors to predict poor or degrading performance. To increase the effectiveness of monitoring tools, a number of automated methods to notify maintenance and plant engineers based on pre-specified process conditions is suggested.

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GLOSSARY

AT: Analysis Time; **CO:** Controller Output; **DCS:** Digital (Distributed) Control System; **DDE:** Dynamic Data Exchange; **EU:** Engineering Unit; **HDOPC:** Historical Data OPC; **ODBC:** Open Database Connectivity; **OPC:** OLE for Process Control; **PDLPM:** Process Diagnostics and Loop Performance Monitoring; **PLC:** Programmable Logic Controller; **PV:** Process Variable; **SP:** Setpoint; **XML:** Extensible Markup Language.

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