

MODERN MAINTENANCE APPROACHES IN PROCESS ANALYTICS: BRIDGING SCHEDULED INTERVENTIONS AND DATA-DRIVEN CONDITION MONITORING

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ABSTRACT

Maintenance strategies in process analytics are evolving as facilities seek higher reliability, reduced downtime and improved long-term asset performance. Modern maintenance now extends beyond routine service and corrective repair, supported by connected ecosystems that combine machine sensors, production data and analytical evaluation. With global interest in predictive maintenance growing at annual rates approaching 30%, the shift toward more condition-oriented approaches is accelerating across many industrial environments. Preventive maintenance remains essential for addressing known degradation mechanisms through scheduled interventions. Complementing this, condition-based and predictive concepts use health indicators, chromatographic or spectroscopic performance trends and process parameters to detect early signs of drift, contamination or mechanical wear. These data-informed insights enable maintenance actions that more closely reflect the actual condition of analyzers and related systems. Trend analysis and pattern-recognition techniques provide additional support for identifying subtle anomalies, enhancing early detection without displacing fundamental maintenance principles. A consistent and structured maintenance methodology helps align preventive and predictive elements, improving resource efficiency, analyzer availability and long-term data integrity across diverse fleets. This paper will outline the practical considerations and emerging techniques that support broader adoption of preventive and predictive maintenance approaches within process analytics.

1. INTRODUCTION

Process analytics systems are essential components in modern industrial plants, providing critical input for process control, product quality, safety and regulatory compliance. The continuous availability and accuracy of analyzers directly influence operational stability and decision-making across a wide range of industries.

Industrial production environments are increasingly characterized by higher automation levels, tighter efficiency targets and growing cost pressure. Process analyzers are therefore expected to operate reliably with minimal manual intervention, while continuous availability and stable measurement performance have become standard requirements. Traditional time-based maintenance and corrective approaches remain relevant but are often insufficient to meet current demands for uptime, operational resilience and data integrity. Advances in sensor technology, connectivity and data acquisition now enable more proactive management of analyzer condition. Within this evolving landscape, preventive maintenance continues to address known aging mechanisms through scheduled interventions. Complementing this foundation, condition-based and predictive approaches use performance indicators and operational data to detect emerging issues such as drift, contamination or mechanical wear. These concepts allow maintenance activities to be aligned more closely with actual analyzer condition rather than fixed schedules alone.

The integration of preventive, condition-based and predictive strategies forms the basis of modern maintenance frameworks in process analytics. By combining structured interventions with data-driven condition assessment and forward-looking insights, organizations can improve analyzer availability, resource efficiency and long-term measurement reliability in increasingly automated industrial environments.

2. TERMINOLOGY

The following terms are used throughout this paper to describe maintenance strategies, enabling technologies and operational concepts:

Preventive Maintenance:

Scheduled maintenance activities performed at predefined intervals to address known aging mechanisms and reduce the likelihood of equipment failure.

Condition-Based Maintenance:

Maintenance triggered by measured equipment condition or performance indicators rather than fixed schedules.

Predictive Maintenance:

Data-driven maintenance approach that uses historical and real-time performance information to identify emerging degradation and estimate future maintenance needs.

Analyzer Health Indicators:

Quantitative metrics derived from analyzer performance, diagnostics or process data that reflect instrument condition and stability.

Data-Driven Maintenance:

Maintenance strategies informed by systematic collection and analysis of operational data rather than solely by time-based schedules.

IoT / IloT (Internet of Things / Industrial Internet of Things):

Networked architectures that enable sensors, instruments and systems to exchange operational data across industrial environments.

Digital Data Chain:

End-to-end data flow from field devices through acquisition, storage and analytics platforms, supporting continuous condition assessment.

Remote Monitoring / Remote Service:

Capabilities that enable off-site observation, diagnostics and support of equipment using connected systems.

Operational Technology (OT):

Hardware and software used to monitor and control industrial processes and physical equipment.

Cybersecurity:

Measures designed to protect connected industrial systems, data integrity and operational continuity.

Maintenance terminology and data classification in industrial environments are commonly aligned with international standards, including ISO 14224 for reliability and maintenance data, ISO 55000/55001 for asset management, ISO 17359 and ISO 13381 for condition monitoring and prognostics, IEC 61508/61511 for functional safety, and NIST frameworks for cybersecurity in connected industrial systems. (5-11)

3. MAINTENANCE STRATEGIES IN PRACTICE

Maintenance strategies in industrial environments have evolved from reactive repair toward structured preventive programs and, more recently, toward condition-informed and data-driven approaches. Rather than representing mutually exclusive paradigms, modern maintenance frameworks combine multiple strategies to address different aspects of equipment reliability and performance.

3.1 EVOLUTION AND INTEGRATED MAINTENANCE FRAMEWORK

Historically, maintenance activities were predominantly reactive, with interventions performed after failures occurred. Preventive maintenance introduced structured, time-based service to address predictable wear mechanisms. Condition-based maintenance linked interventions to observable performance indicators, while predictive maintenance extended these concepts through trend analysis and data-driven forecasting of emerging degradation. Proactive maintenance complements these approaches by addressing root causes through process optimization and

system-level improvements. Together, these models form an integrated framework that aligns maintenance actions with analyzer condition and long-term system performance.

3.2 MAINTENANCE PARADIGMS AND CHARACTERISTICS

Each maintenance strategy is distinguished by its primary trigger, information basis and operational objective. Table I summarizes the key characteristics of commonly applied maintenance paradigms. (5, 7)

Reactive maintenance is triggered by failure events and focuses on restoring functionality through repair or replacement. Preventive maintenance relies on scheduled inspections and servicing to reduce predictable wear. Condition-based maintenance initiates actions when defined health indicators exceed thresholds. Predictive maintenance uses historical and real-time data to anticipate degradation and support forward-looking intervention planning. Proactive maintenance targets root causes through system-level improvements.

While these approaches differ in execution, effective maintenance frameworks typically combine multiple paradigms to balance reliability, efficiency and resource utilization.

TABLE I. OVERVIEW OF MAINTENANCE PARADIGMS AND THEIR DEFINING CHARACTERISTICS

Strategy	Trigger	Basis	Typical Methods	Primary Objective
Reactive Maintenance	Failure event	Equipment breakdown	Repair, replacement	Restore functionality
Preventive Maintenance	Scheduled intervals	Time and usage	Planned inspections, servicing	Prevent unplanned failure and maintain reliable operation
Condition-Based Maintenance	Threshold exceedance	Health indicators	Performance monitoring	Align actions with actual condition
Predictive Maintenance	Trend development	Historical and real-time data	Forecasting, anomaly detection	Anticipate failures
Proactive Maintenance	Root causes	System behavior	Process optimization, design improvement	Eliminate failure mechanisms

3.3 REACTIVE MAINTENANCE

Reactive maintenance refers to corrective actions performed after equipment failure or significant performance degradation has already occurred. While unavoidable in certain scenarios, reactive approaches typically result in unplanned downtime and higher overall maintenance costs. In process analytics, purely reactive strategies are generally unsuitable due to the critical role analyzers play in continuous operation and compliance-related measurements.

3.4 PREVENTIVE MAINTENANCE

Preventive maintenance is based on scheduled interventions performed at predefined intervals, independent of immediate analyzer condition. Activities are informed by manufacturer recommendations, historical experience and known aging mechanisms. Typical measures include replacement of consumables, calibration checks, cleaning procedures and functional inspections.

The primary objective is to reduce failure probability by addressing predictable degradation before performance is affected. While interval-based maintenance cannot account for all operational variability, it provides a structured foundation for maintaining system reliability.

3.5 CONDITION-BASED MAINTENANCE

Condition-based maintenance links interventions to observed changes in analyzer performance or health indicators rather than fixed schedules alone. For chromatographic analyzers, practical indicators include retention time shift (Δt versus SOP reference), baseline noise and tilt (σ , dB/dt), peak symmetry (tailing factor), detector response stability (e.g., FID response factor (RF) and signal-to-noise ratio (SNR)), and leak or flow stability within the sample system. Each indicator should be mapped to plausible failure modes such as leaks, contamination, column aging or carrier gas purity issues, and validated for trend consistency, diagnostic value and false-alarm rate. (7)

By tracking these indicators over time, maintenance actions can be initiated when deviations exceed defined thresholds or trends suggest emerging degradation, improving responsiveness while reducing unnecessary service activities.

3.6 PREDICTIVE MAINTENANCE

Predictive maintenance builds upon condition-based monitoring by incorporating historical and real-time data to anticipate future degradation or failure. Instead of reacting solely to threshold exceedances, predictive approaches identify trends, patterns or anomalies that indicate increasing probability of upcoming performance issues.

In process analytics, predictive maintenance leverages long-term analyzer trends, operational context and environmental influences to estimate remaining useful

performance and optimize intervention timing. When effectively implemented, predictive methods support forward-looking planning and contribute to reduced unplanned downtime.

3.7 PROACTIVE MAINTENANCE

Proactive maintenance focuses on eliminating underlying causes of degradation rather than responding to symptoms alone. Through root cause analysis, process optimization and design or installation improvements, proactive strategies reduce recurring stress factors that drive wear and instability. Rather than replacing predictive maintenance, proactive approaches translate identified risk patterns into long-term system improvements that enhance sustained reliability.

3.8 MAINTENANCE MISCONCEPTIONS

Despite increasing adoption of advanced maintenance concepts, several misconceptions persist. Maintenance is often viewed primarily as a cost center, although effective strategies significantly reduce downtime and extend asset lifetime. Preventive and predictive maintenance are sometimes treated as interchangeable despite their fundamentally different information bases. Increased data availability alone does not guarantee improved outcomes without engineering context, and analytical tools augment rather than replace domain expertise.

4. DRIVERS FOR PREDICTIVE MAINTENANCE ADOPTION

The increasing adoption of predictive maintenance reflects broader technological and operational changes across asset-intensive industries. While preventive and condition-based approaches remain essential components of maintenance frameworks, several converging drivers are accelerating the shift toward data-driven and forward-looking maintenance strategies.

4.1 INCREASING AUTOMATION AND AUTONOMOUS OPERATION

Industrial environments are evolving toward higher levels of automation and autonomous operation. Process plants increasingly rely on continuous, self-regulating systems that are expected to operate reliably with minimal manual intervention.

Predictive maintenance supports these operational models by enabling earlier detection of emerging performance deviations and facilitating planned interventions before disruptions occur. As analyzer systems become more tightly integrated into automated process control architectures, forward-looking maintenance capabilities support operational continuity.

4.2 ECONOMIC IMPACT OF DOWNTIME AND COST REDUCTION

Unplanned downtime remains a material economic driver across asset-intensive industries, but reported costs span orders of magnitude depending on sector, plant size, and operating model. Multi-industry analyses commonly cite average figures in the hundreds of thousands of US dollars per hour (\approx USD 260k/h as an indicative cross-industry benchmark), while recent surveys of smaller facilities report values around USD 25k/h and large plants $>$ USD 500k/h; in tightly coupled, high-throughput automotive environments, examples above USD 2M/h have been reported (1–3).

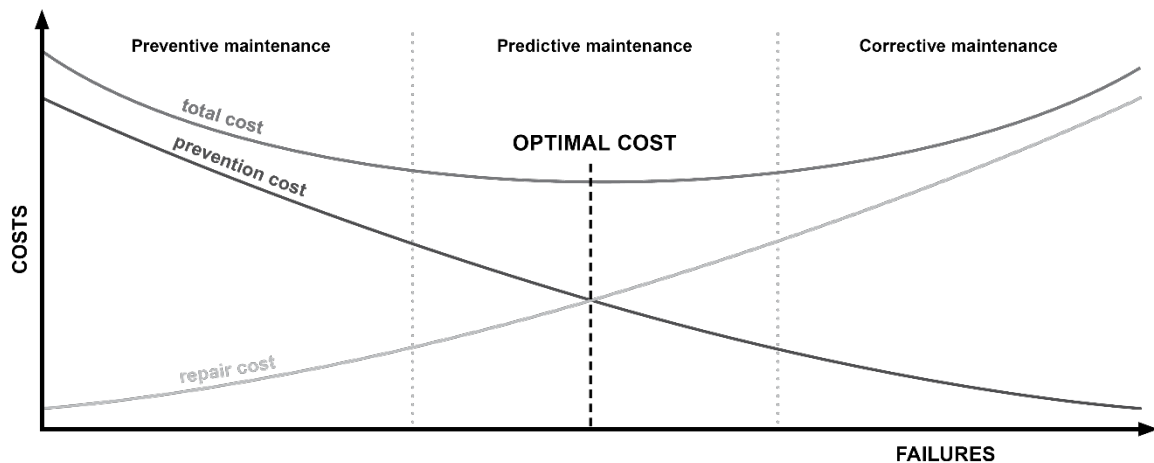


FIGURE 1. MAINTENANCE COST TRADE-OFF ACROSS PREVENTIVE, PREDICTIVE AND CORRECTIVE STRATEGIES.

Rather than emphasizing absolute cost figures alone, predictive maintenance focuses on optimizing the balance between preventive effort and repair cost by aligning maintenance actions with anticipated equipment behavior (Figure 1). This enables reduction of unnecessary time-based interventions while supporting targeted scheduling based on actual risk.

4.3 ADVANCES IN DATA AVAILABILITY AND ANALYTICS

Advances in sensor technology, connectivity and data acquisition have significantly increased the availability of high-resolution operational data. In parallel, analytical methods enable identification of trends, anomalies and performance patterns across complex equipment fleets.

These developments provide the technical foundation for predictive maintenance by transforming measurement data into actionable insights. Their primary value lies in supporting maintenance decision-making and engineering assessment rather than replacing domain expertise.

4.4 WORKFORCE EVOLUTION AND REMOTE OPERATIONS

Maintenance organizations are adapting to increasing system complexity, geographically distributed assets and limited availability of specialized personnel. These factors drive greater reliance on remote diagnostics and centralized support models.

Predictive maintenance facilitates these approaches by providing continuous visibility into analyzer conditions without requiring permanent on-site presence. Combined with remote monitoring capabilities, data-driven assessment tools enable maintenance teams to prioritize interventions and coordinate service activities more efficiently across dispersed installations.

4.5 STRATEGIC SHIFT FROM PREVENTIVE TO PREDICTIVE MAINTENANCE

Taken together, automation trends, economic pressures, enhanced data accessibility and evolving workforce models are driving a strategic shift from predominantly preventive maintenance toward predictive frameworks. Rather than replacing existing practices, predictive maintenance augments preventive and condition-based strategies by introducing forward-looking capabilities that align maintenance planning with anticipated equipment behavior.

These drivers define the requirements for modern maintenance architecture and motivate the technical enablers discussed in the following section.

5. TECHNICAL ENABLERS FOR PREDICTIVE MAINTENANCE

Predictive maintenance relies on reliable access to performance data, system connectivity and analytical capabilities that support forward-looking decision-making. Translating these requirements into practical maintenance frameworks depends on interconnected technical enablers that support data collection, transmission, analysis and interpretation across industrial environments.

5.1 SENSOR TECHNOLOGY AND IOT NETWORKS

Sensor technology and industrial IoT networks provide the foundation for condition monitoring and predictive analysis. Sensors capture relevant performance and health parameters, which are transmitted to data acquisition systems for storage and evaluation. High-resolution, synchronized datasets are essential for identifying subtle deviations that may precede functional degradation.

For predictive maintenance applications, consistent sensor performance and reliable data transmission are critical, as trend analysis and anomaly detection depend on continuous, high-quality input over extended operating periods.

5.2 DATA ACQUISITION AND DIGITAL DATA CHAINS

Effective predictive maintenance requires structured data acquisition and integration across distributed assets. Digital data chains connect sensor outputs with acquisition systems, storage platforms and analytical tools, enabling seamless flow of performance information from field devices to centralized evaluation environments.

Time-stamped and contextualized datasets support historical trend comparison and identification of emerging performance changes. Integration of analyzer measurements with process conditions further improves interpretability and diagnostic relevance.

Another important enabler for predictive maintenance in process analyzers is the implementation of automated validation procedures. In addition to continuous monitoring of critical variables, automated validation routines provide regular confirmation of analyzer performance without requiring manual intervention. These functions improve confidence in measurement data, support early detection of performance deviations and enhance the reliability of condition-based and predictive maintenance strategies. In highly automated environments, automated validation contributes to stable operation by ensuring that diagnostic and predictive evaluations are based on verified analyzer performance.

5.3 CONNECTIVITY AND COMMUNICATION INFRASTRUCTURE

Robust communication architecture ensures reliable transmission of condition data from field devices to analytical platforms. Depending on system design, preliminary processing may occur at the edge, with aggregated information forwarded to centralized systems for long-term evaluation.

Connectivity strategies must balance latency, bandwidth, availability and security while enabling remote monitoring and diagnostics. Scalable communication frameworks support aggregation of condition data from multiple analyzers, facilitating fleet-level assessment and coordinated maintenance planning.

5.4 ANALYTICS AND PATTERN RECOGNITION

Analytics engines apply statistical methods, pattern recognition and machine learning techniques to historical and real-time performance data. These capabilities support trend identification, anomaly detection and estimation of future degradation, providing early indicators for forward-looking maintenance decisions.

Analytics augment diagnostic capabilities by highlighting subtle changes in system behavior. Selection of appropriate analytical techniques depends on equipment type, operating context and available data.

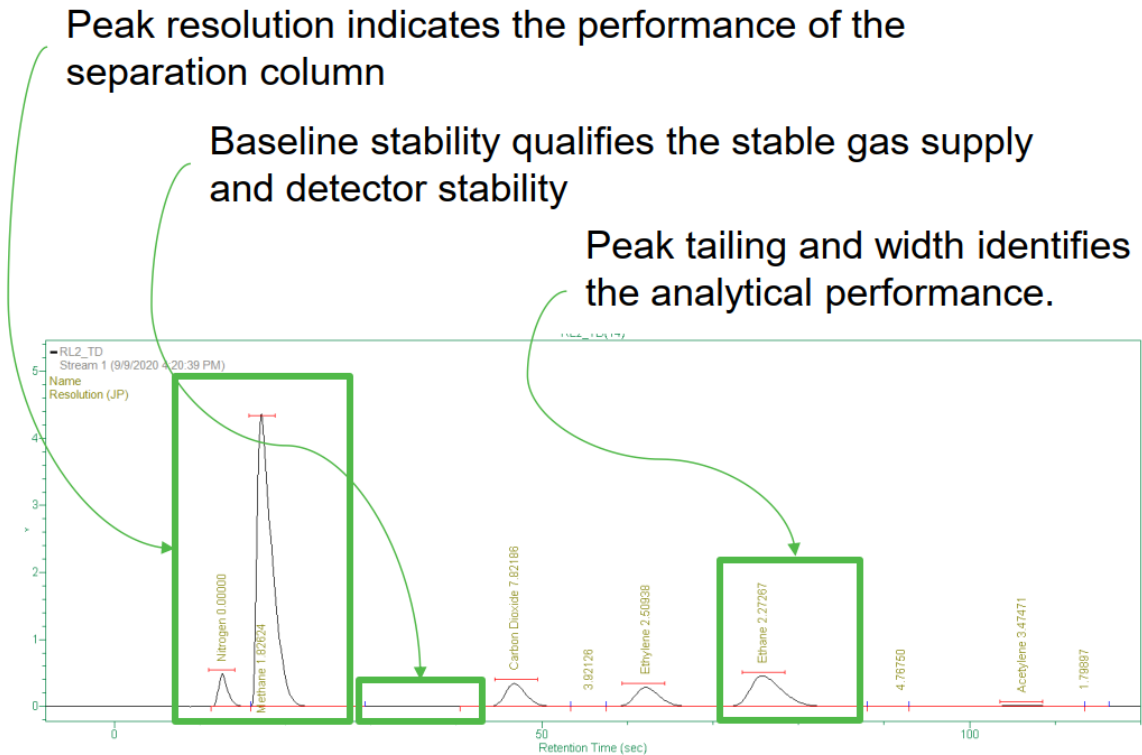


FIGURE 2. CHROMATOGRAPHIC PERFORMANCE INDICATORS AS INPUT SIGNALS FOR CONDITION MONITORING AND PREDICTIVE ANALYSIS

In line with international guidance, ISO 17359 provides general procedures for establishing condition-monitoring programs (indicator definition, acquisition routes, validation), while ISO 13381-1 defines requirements and concepts for prognostics including trend consistency and uncertainty handling (7, 8).

5.5 VISUALIZATION AND DECISION SUPPORT

Visualization platforms, dashboards and alerting mechanisms translate analytical results into actionable information. Trend charts, threshold-based warnings and decision-support indicators help maintenance teams assess condition status and prioritize interventions.

In predictive maintenance workflows, decision-support tools enable prioritization based on anticipated risk and remaining useful performance, supporting proactive scheduling and improved allocation of maintenance resources.

6. IMPLEMENTATION CONSIDERATIONS

While predictive and condition-based maintenance offer significant potential, successful implementation depends on more than technology alone. Practical

deployment requires alignment of data quality, system integration, organizational readiness and cybersecurity within existing operational frameworks.

6.1 DATA QUALITY AND INTEGRATION

Reliable maintenance insights depend on consistent, high-quality data. Sensor accuracy, signal stability and time synchronization across data sources directly influence analytical reliability. Incomplete or poorly contextualized datasets limit predictive performance and may lead to ambiguous recommendations.

Predictive maintenance commonly requires integration of analyzer data with process information and historical maintenance records. Standardized interfaces and data governance practices support interoperability and ensure representative operating context. Incremental implementation—starting with clearly defined indicators and limited asset scopes—helps validate data pipelines before broader deployment.

6.2 ORGANIZATIONAL READINESS AND WORKFLOW INTEGRATION

Technical infrastructure alone does not guarantee successful adoption of advanced maintenance strategies. Maintenance teams must integrate analytical insights into existing workflows through clearly defined responsibilities, escalation paths and alignment with operational priorities.

Predictive maintenance also influences skill requirements, as personnel increasingly engage in diagnostic and analytical tasks alongside traditional service activities. Targeted training and cross-functional collaboration between maintenance, operations and IT/OT teams support effective interpretation of condition data and translation into actionable interventions.

6.3 CYBERSECURITY AND OT SECURITY

Connected maintenance architectures rely on networked data flows, remote monitoring and system connectivity that extend beyond local environments. While these capabilities enhance maintenance decision-making, they introduce cybersecurity risks that must be managed to protect analyzer integrity and operational continuity.

OT-aware security frameworks such as NIST SP 800-82 and NIST SP 800-53 provide structured guidance for network segmentation, secure remote access and integrity protection. Effective cybersecurity strategies combine technical controls—including authentication, access management and encryption—with organizational practices such as risk assessment and incident response planning.

In industrial environments, availability and safety are primary objectives alongside data integrity. Legacy devices and heterogeneous networks emphasize the importance of security-by-design approaches that integrate protection mechanisms early in system architecture. (10,11)

7. DISCUSSION

The transition toward data-informed maintenance reflects a broader shift in industrial asset management driven by increasing automation, operational complexity and economic pressure. In process analytics, preventive, condition-based, predictive and proactive maintenance should be viewed as complementary elements within an integrated framework rather than isolated methodologies.

Predictive maintenance increasingly serves as a central driver by enabling forward-looking planning based on performance trends and emerging anomalies. When combined with proactive strategies that address underlying failure mechanisms, predictive approaches support sustained reliability improvements beyond individual maintenance cycles and extend traditional maintenance practices toward continuous performance optimization.

Economic considerations reinforce this development. Unplanned downtime represents a significant operational risk, highlighting the importance of maintenance strategies that move beyond reactive response. By aligning maintenance actions with anticipated equipment behavior, predictive approaches enable targeted interventions, reduce unnecessary service activities and improve lifecycle cost management.

Empirical reports indicate that predictive maintenance can reduce maintenance costs and unplanned downtime compared with reactive strategies. Beyond direct economic impact, predictive and condition-based approaches contribute to operational resilience by supporting earlier diagnosis and proactive intervention in increasingly automated environments. (4)

In practical applications, integrated maintenance strategies typically combine scheduled preventive service with condition monitoring and trend evaluation of key analyzer performance indicators. For example, chromatographic health parameters such as retention time stability, detector response and flow conditions may be continuously monitored, while scheduled interventions are retained for components with known aging mechanisms. Such combined approaches allow maintenance actions to be prioritized based on actual equipment condition while preserving the reliability benefits of structured service intervals. Conceptual architectures often include sensor data acquisition, centralized analytics platforms and remote diagnostic access, enabling coordinated maintenance decisions across distributed analyzer fleets. Even when implemented at a basic level, integrated maintenance strategies can reduce unnecessary service activities, limit unplanned downtime and improve overall lifecycle cost efficiency.

The evolving role of maintenance personnel further underscores this transformation. Analytical tools augment engineering expertise by providing enhanced visibility into system behavior, while effective outcomes continue to depend on domain knowledge and contextual interpretation. Human–machine collaboration therefore remains central to data-driven maintenance.

Finally, cybersecurity considerations shape the practical boundaries of predictive maintenance adoption. As connectivity expands across industrial environments, protecting analyzer data and operational systems becomes integral to maintaining trust in data-driven maintenance frameworks. Secure system design and OT-aware governance practices represent essential components of sustainable predictive maintenance strategies.

8. CONCLUSION AND OUTLOOK

Modern maintenance in process analytics extends beyond routine service and corrective repair. While preventive maintenance continues to provide a structured foundation for addressing known degradation mechanisms, condition-based and predictive approaches introduce additional layers of insight that align maintenance activities more closely with actual analyzer condition.

Predictive maintenance increasingly acts as a key driver by enabling forward-looking planning based on performance trends and emerging anomalies. When complemented by proactive strategies that address underlying failure mechanisms, predictive approaches support sustained reliability improvements and long-term system stability. Together, these concepts extend traditional maintenance models toward continuous performance optimization in increasingly automated industrial environments.

Advances in sensor technology, connectivity, analytics and digital data chains enable more data-informed maintenance paradigms. At the same time, successful implementation depends on organizational readiness, data quality and robust cybersecurity practices. Predictive maintenance should therefore be approached as a system-level capability integrating technology, processes and engineering expertise.

Looking ahead, maintenance strategies are expected to evolve toward connected ecosystems supporting remote diagnostics, assistive inspection technologies and deeper integration between maintenance and operations. Analytical tools will increasingly augment the diagnostic role of maintenance personnel, enabling earlier detection of emerging issues and more informed planning of interventions. As industrial environments continue to prioritize availability, operational resilience and cost efficiency, predictive maintenance will play an increasingly strategic role in supporting stable and adaptive process analytics.

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