

# **Digital Predictive Maintenance Monitoring Systems in the Process Industry: State of the Art and Research Directions**

**Lucian NEGRUȚ<sup>1</sup>, Constantin BUNGĂU<sup>1</sup>**

1 University of Oradea, Faculty of Management and Technological Engineering,  
str.Universității nr.1, Oradea 410087, Romania

negrut.lucianiosif@student.uoradea.ro

**Abstract.** Predictive maintenance is a key strategy in the process industry, aiming to reduce unplanned downtime, optimize maintenance resources, and improve operational safety through early detection of equipment degradation. Digital monitoring systems based on industrial sensors and Supervisory Control and Data Acquisition (SCADA) / Distributed Control System (DCS) infrastructures enable continuous condition assessment of critical assets. This paper presents an extended review of digital predictive maintenance monitoring systems in the process industry, focusing on system architectures, multisensor monitoring, condition indicators, data processing approaches, and current research directions. The presented analysis supports the implementation of a digital predictive maintenance monitoring system within doctoral research.

**Keywords:** predictive maintenance; condition monitoring; process industry; SCADA; DCS; digital monitoring systems

## **1. Introduction**

The processing industry includes sectors such as chemical processing, oil and gas, power generation, food processing, and pharmaceuticals, all of which rely on complex and capital-intensive equipment operating under continuous and often harsh conditions. Unexpected failures of pumps, compressors, heat exchangers, reactors, and auxiliary systems may result in significant production losses, safety incidents, and environmental impact. Traditional corrective and time-based preventive maintenance strategies are increasingly insufficient, as they do not accurately reflect the actual condition and degradation state of industrial assets [1].

Predictive maintenance addresses these limitations by continuously monitoring operational parameters and anticipating failures based on trends and deviations from normal operating conditions [2]. By shifting maintenance activities from reactive or calendar-based interventions to condition-based decisions, predictive maintenance enables improved asset availability, reduced lifecycle costs, and enhanced process reliability.

## 2. Digital Monitoring Systems in the Process Industry

Modern industrial plants are equipped with SCADA and DCS, which collect real-time and historical process data from distributed sensors and field devices [3]. These systems provide time-stamped and validated datasets that form the backbone of digital monitoring platforms used for predictive maintenance and operational decision support [4].

Beyond basic data acquisition, SCADA and DCS platforms perform essential functions such as alarm management, data validation, signal filtering, and historian services. Industrial historians store large volumes of time-series data over long periods, enabling long-term trend analysis and retrospective investigation of equipment behavior. Such capabilities are critical for identifying gradual degradation phenomena that may not be detectable through short-term observation.

In the context of predictive maintenance, SCADA/DCS infrastructures facilitate the integration of condition monitoring data with process variables, allowing correlations between operating regimes and equipment health to be established. For example, changes in vibration or temperature levels can be analyzed in relation to process load, pressure or flow conditions, improving the interpretability of condition indicators.

Another important aspect is the role of SCADA and DCS systems in ensuring data reliability and traceability. Industrial control systems typically implement redundancy, synchronization mechanisms, and quality flags, which help distinguish valid measurements from faulty sensor readings or communication errors. This is particularly relevant for predictive maintenance applications, where inaccurate or incomplete data may lead to false alarms or missed detections. Furthermore, modern digital monitoring architectures increasingly support standardized communication protocols and interfaces, enabling interoperability between control systems, condition monitoring tools, and higher-level maintenance management platforms. This interoperability allows predictive maintenance functions to be integrated into existing operational workflows, supporting informed decision-making and coordinated maintenance planning across the plant.

## 3. Multisensor Condition Monitoring

Predictive maintenance systems rely on multisensory condition monitoring to capture complementary aspects of equipment behavior and degradation processes. Vibration analysis is widely used for rotating machinery diagnostics, enabling the detection of imbalance, misalignment, bearing defects, and gear wear. In parallel, temperature, pressure, and flow monitoring provide valuable insight into thermal stress, lubrication conditions, and fluid-related degradation mechanisms [2].

Different sensor types exhibit varying sensitivity to specific fault modes and operating conditions. For instance, vibration sensors are particularly effective in detecting mechanical faults at an early stage, whereas temperature and pressure sensors may indicate more advanced degradation or abnormal process conditions. Electrical measurements, such as current and power consumption, can further reflect changes in mechanical load or efficiency, especially in motor-driven equipment.

The integration of multiple sensing modalities enhances fault detectability and diagnostic robustness by reducing the dependence on a single measurement source. Multisensor approaches allow cross-validation of condition indicators, improving confidence in detected anomalies and minimizing the likelihood of false alarms caused by sensor noise or transient process disturbances.

From an implementation perspective, multisensory condition monitoring requires careful consideration of sensor placement, sampling frequency, and data synchronization. Sensors must be strategically positioned to capture relevant physical phenomena, while synchronized acquisition ensures

that correlations between different measurements can be accurately established. These aspects are particularly important in continuous processing industries, where operating conditions may vary over time.

Overall, multisensory condition monitoring provides a comprehensive representation of equipment health, forming a reliable foundation for condition-based maintenance strategies and supporting informed maintenance planning decisions in complex industrial environments.

#### 4. Condition Indicators and Data Processing

Raw sensor signals acquired from industrial equipment are typically transformed into condition indicators that provide a more compact and interpretable representation of equipment health. This transformation is necessary due to the high volume, variability, and noise often present in raw measurement data. Commonly used indicators include vibration root mean square (RMS) values, spectral amplitudes at characteristic frequencies, temperature gradients, pressure deviations from nominal operating conditions, and statistical descriptors derived from time-series signals [1].

Condition indicators enable the monitoring of equipment behavior over extended periods, supporting the identification of gradual degradation processes that may not be evident in instantaneous measurements. Trend analysis plays a central role in this context, allowing maintenance personnel to observe long-term changes and assess whether operating parameters remain within acceptable limits. Gradual upward trends, increasing variability, or sudden shifts in indicator values may signal emerging faults or abnormal operating conditions.

Threshold-based alarm systems remain widely applied in industrial practice due to their transparency, simplicity, and ease of implementation. Alarm thresholds are typically defined based on manufacturer recommendations, historical operating data, or industry standards. However, static thresholds may be insufficient in environments characterized by varying operating regimes, which has motivated the use of adaptive limits and contextual evaluation of condition indicators.

In addition to individual indicator monitoring, data processing approaches increasingly focus on the correlation and aggregation of multiple indicators to provide a more comprehensive assessment of equipment condition. By jointly analyzing vibration, thermal, and process-related indicators, it is possible to distinguish between load-related variations and genuine degradation phenomena. Such integrated analysis supports more reliable condition assessment and reduces the likelihood of misinterpretation caused by isolated measurements.

Overall, the systematic processing of sensor data into meaningful condition indicators represents a fundamental component of digital predictive maintenance systems. It bridges the gap between raw measurements and actionable maintenance information, enabling condition-based decision-making while remaining compatible with established industrial monitoring practices.

#### 5. State of the Art in Predictive Maintenance Systems

Commercial predictive maintenance solutions integrate sensor networks, data acquisition hardware, and software platforms for data visualization, reporting, and alert generation. These systems typically provide dashboards for real-time condition monitoring, historical data analysis, and alarm management, supporting maintenance planning and operational decision-making. Many solutions are designed to operate on top of existing SCADA and DCS infrastructures, thereby minimizing integration effort and capital investment while leveraging already available process data [3].

In industrial practice, state-of-the-art predictive maintenance systems emphasize reliability, transparency, and ease of use. Visualization tools often include trend plots, condition indicator summaries, and alarm histories, enabling maintenance personnel to quickly assess equipment status. Reporting functionalities support maintenance documentation, compliance with regulatory

requirements, and communication between operational and maintenance teams. These features are particularly important in the process industry, where maintenance decisions may have safety and environmental implications.

From a research perspective, significant efforts have been directed toward improving diagnostic performance under realistic industrial conditions. Studies address challenges such as noisy measurements, incomplete datasets, and variability in operating regimes. Emphasis is placed on robust signal processing techniques, sensor redundancy, and validation methods to ensure that condition assessments remain reliable despite disturbances inherent to industrial environments [2].

Scalability represents another key aspect of state-of-the-art predictive maintenance systems. Large process plants may involve hundreds or thousands of monitored assets, requiring architectures capable of handling high data volumes and supporting incremental system expansion. Research contributions therefore explore modular system designs and standardized interfaces that facilitate deployment across diverse equipment types and process units [5].

Overall, the current state of the art reflects a convergence between industrial solutions and academic research, focusing on practical applicability, system robustness and integration within existing operational frameworks. These trends provide a solid foundation for the development and implementation of advanced digital predictive maintenance monitoring systems in the process industry.

## 6. Challenges and Research Directions

Despite significant progress in digital predictive maintenance technologies, several challenges continue to limit their widespread and effective implementation in the process industry. One of the primary challenges relates to reliable data acquisition under harsh industrial conditions. Sensors are often exposed to high temperatures, vibrations, humidity, or corrosive environments, which may affect measurement accuracy and long-term stability. Ensuring sensor durability and consistent data quality remains a critical requirement for dependable condition monitoring [4].

Another major challenge involves interoperability with legacy systems. Many industrial facilities operate heterogeneous control infrastructures composed of equipment from different vendors and generations. Integrating predictive maintenance functionalities into such environments requires standardized interfaces, compatible communication protocols, and careful system configuration to avoid disruptions to existing operations. Limited interoperability can hinder data exchange and restrict the scalability of monitoring solutions.

Compliance with industrial standards and regulations represents an additional constraint, particularly in safety-critical process industries. Predictive maintenance systems must align with established norms related to condition monitoring, data management, and system reliability. Adhering to these standards is essential to ensure acceptance by operators and to support traceability and auditability of maintenance decisions.

Future research directions increasingly focus on the development of modular and flexible system architectures that facilitate incremental deployment and adaptation to different equipment types. Such architectures enable predictive maintenance solutions to be tailored to specific process units while maintaining a consistent system framework across the plant.

Further research is also directed toward the refinement of condition indicators that are robust to operational variability and capable of capturing early-stage degradation phenomena. Improved indicator definition and validation can enhance the sensitivity and reliability of condition assessments, supporting more effective maintenance planning.

Finally, closer integration between predictive maintenance systems and computerized maintenance management systems (CMMS) is identified as a key research direction. Seamless integration enables condition-based information to be directly linked to maintenance scheduling,

resource allocation, and documentation processes, thereby enhancing the overall efficiency and effectiveness of maintenance operations.

## 7. Conclusions

The paper has reviewed the state of the art in digital predictive maintenance monitoring systems for the process industry. Multisensor monitoring combined with digital control infrastructures enables early detection of equipment degradation and supports informed maintenance decisions.

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