NIST Industry Forum: Monitoring, Diagnostics, and Prognostics for Large Manufacturing Operations

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The Boeing Company

Boeing is the leading manufacturer of commercial jetliners and defense, space, and security systems.

A top U.S. exporter, the company supports airlines and U.S. and allied government customers in 150 countries.

Boeing employs more than 160,000 people across the United States and in more than 65 countries.
The 787 Dreamliner family

- Innovative and efficient airplane family
- Offers 20-25 percent better fuel per seat and emissions than the airplanes it replaces

- Comfort and convenience for passengers
- Profitability and flexibility for airlines
- Exceptional environmental performance for everyone
777X benefits from key technologies

- Folding wing tip for airport compatibility
- New interior with wider cabin
- New flight deck
- New composite wing with 72 m span
- All new GE9X engine
- Natural laminar flow nacelle
Network Data Model for Manufacturing

1. Data Acquisition Framework – Sensors & DAQ Modules
2. Communication system
3. Data Analytics
4. Interface to backend systems & portal visibility
Strategy: Data Collection and Interface between ISA-95 Levels 0 to 4

- **L0**: Physical Production Process
- **L1**: Real-time Sensing and Manipulation (e.g., Vision, Identification, Location, Actuation)
- **L2**: Monitoring & Control (e.g., Robot/Cell Controller, HMI, SCADA)
- **L3**: Manufacturing Operations Management (e.g., MES, Tracking, Work Center Control, Scheduling)
- **L4**: Enterprise Systems (e.g., PLM, ERP, SCM, Shipping/Receiving)

**Interactions**:
- Manufacturing Operations Management (MOM) provides manufacturing execution instructions to work cell PC
- MOM receives manufacturing process data from Data Collector PC

**Key Points**:
- Machine Performance & Health Data Available on Day 1
- Standard Format
- Standard Interface
- ISA-95 Model, Networks, and Information Flow
Equipment Data Flow Architecture “Boeing Model”

Manufacturing Operations Management
- Pilot projects for proof of concept
- Data collections
- Historian interface
- Dashboards
- Lessons learned for production programs

Health Management
- Machine Capability specifications
- Critical Machine Health Data
  - Design Reviews: PDR and CDR
- FMEA Integration
- System installation & commissioning
- Health monitoring algorithms for fault detection
- Reliability plan

Process Control
- Product quality data assessment
- Machine capability assessment vs. engineering requirements
- As built vs. as designed digital twin
- Integration to Production Programs
- Performance to plan

PLC
- Machine Tool Data Agent
- Data Tags & translation

Brick/Front End PC Industry Standard Interface

Sensors Data
- Machine performance data through PLC
- Additional sensor data
- KPI's and important data tags
- Specific process data “Aircraft design and tolerance limits”
Machine Performance & Health Monitoring
“Closed Loop Connected Factory”

**Enterprise Systems**
- PLM
- MOM / MES
- ERP

**Machine Health & Maintenance**
- Machine Learning Intelligence
- Component Health Monitoring: Vibration Analysis, FMEA, Fault Detection

**Data Acquisition Hardware & Firmware**
- OPC-UA, MQTT

**Management Reports**
- Performance Dashboards on Enterprise Network
  - OEE, KPI Status, Material Planning & Usage, Schedule Status, Quality Non-Conformances

**Dashboard & Visualization**

**Business Outcome**
- Predictability
- Reliability
- Quality
- Delivery

**Digital Twin Characteristics Control**
- Program vs. Actual Machine Attributes
- Machine Electrical & Mechanical Systems Functionality vs. Actual Performance
- Machine Calibration, Set-up, N/C Program vs. Actual Recorded Capability & Part Condition
- Simulated vs. Actual Conditions (N/C machining, cutters, kinematics, instrumentation) Context-Based Smart Manufacturing

**Machine Learning Intelligence**

**Business Outcome**

**Digital Twin Characteristics Control**

**Machine Performance & Health Monitoring**

**Production Application Integration**

**Maintenance Ticketing**

**Business Outcome**

- Predictability
- Reliability
- Quality
- Delivery
Machine Health Monitoring Approach – Boeing Model

Start

New Equipment Procurement Specification Review

Operational and Health Data

Identify non-compliance

Return to spec review

FMEA

Operational and Health Data

Categorize Coverage Areas:
- Machine
- Product
- Process

FMEA

Is there sufficient coverage for in-line & post inspections?

No

End

FMEA

Process

Is Machine capable of identifying product requirements?

No

Yes

Detect & Report product quality

Yes

Detect & Report Asset health and status

Add Sensor or methods to detect health and status

No

Product

Is Machine detect primary health and status?

Yes

Detect & Report product quality

Yes

End

OEE & Health Monitoring

Start

Detect & Report Asset health and status

Yes

Exceptional Model

Yes

Historian

Dashboard & Visualization

Front End PC
Composite Laminating Machines Health Management

Automated Fiber Placement for Composite Structures

- Machine coordinate relationship to airplane coordinate
- Capability to trace back error to cause (example: missing tow, gaps, or laps)
- Location of the error in 3D map
- Part centric approach and focus on machine reliability
- Monitoring movements of machine from course, sequence, and layer
- Interface for operator to enter downtime
- Monitoring both multiple parts over one machine or one machine over multiple parts
- Standard time to actual time comparison and % completions (performance to plan)
- Forecasting completions based on past performance data
## FMEA Classification

<table>
<thead>
<tr>
<th>Item Number</th>
<th>Category</th>
<th>Process Step or Variable or Key Input - System</th>
<th>Potential Failure Mode</th>
<th>Potential Effect(s) of Failure</th>
<th>SEV (1-10)</th>
<th>Potential Cause(s) of Failure</th>
<th>OCC (1-10)</th>
<th>Current Process Control (Prevention)</th>
<th>DET (1-10)</th>
<th>RPN (SxOxD)</th>
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**What is the process step?**

The ways or "modes" in which something might fail. In other words, in what ways can the Process Step, Variable, or Key Input go wrong?

**Potential Failure Mode**

What happens when the failure occurs? In other words, what is the impact on the Key Output Variables (customer requirements) or internal requirements?

**Potential Effect(s) of Failure**

How serious is the affect of the failure?

**Potential Cause(s) of Failure**

What causes the Key Input to go wrong? (How could the failure mode occur?)

**Current Process Control (Prevention)**

How frequently does the failure occur?

**Recommended Action**

What are the existing controls that either prevent the failure mode from occurring?

**Frequency or Occurrence of Potential Failure?**

How frequent is cause likely to Occur?

**How probable is Detection of cause?**

How probable is Detection of cause?

**RPN (SxOxD)**

How probable is Detection of cause?

**Current process control (Detection)**

Recommended Action

What are the actions for reducing the Occurrence of the cause, or improving Detection? Should have actions on high RPN's or Severity of 9 or 10.

**Responsibility**

Who's Responsible for the recommended action?

**Actions Taken**

What were the actions implemented? Include completion month/year. (Then recalculate resulting RPN.)

**Target Completion Date**

What is the target completion date?

**Action Complete Date**

Frequency or Occurrence of Potential Failure?

How frequent is cause likely to Occur?

**RPN (SxOxD)**

How probable is Detection of cause?
Machine Learning – Metal Fabrication Center

- Network Drop
- Data Acquisition Modules
- OEE Calculations
- CBM Investigations
  - Trend Analysis & Comparisons with the Past History
  - Spectrum Analysis:
    - FFT, Time Domain, Frequency Domain, and Peak Rate Analysis
- Machine Problems
  - Spindle Faults
  - Axes Motors
  - Sub-Components Mechanical or Electrical Systems Failures
- Corrective Actions

Key Objectives
- Understand and determine what data to collect
- Signals representing functional degradations
- Software application and intelligence to detect faults before they occur
- Actions to mitigate failures
- Fault history and best practices plans
Machine Monitoring – Assembly Automation Systems

- Network drops & connectivity
- Data Collections & Quality Status
  - Hole or fastener data
  - OEE
- Machine Health Data
  - Tool Tip & Spindle Monitoring
  - Motion System
  - Tools & Holding Fixtures
  - Mechanical Components
- Data Analytics
  - CBM
  - Calibration
  - Part Quality
  - Throughput
- Non Conformance & Corrective Actions
Infrastructure Health Monitoring
Cranes, Power, Compressed Air, Vacuum, HVAC

Vibration, Power Quality, Temperature, Humidity, Alignment

Fault detection and time to failure

Wireless sensors can be used as needed and moved around

On-line Power Monitoring

PLC and data acquisition system

Wireless Capability Eliminates Cabling costs and can be installed in remote locations
Sensor Based Process Monitoring and Safety Systems
Environmental Monitoring: Freezer Health

Walk-in Freezer Material Location & Age Tracking

Temperature Recorder, Min/Max Data, Data History
777X Continuous Clean Room Monitoring System – Deployed in Multiple Sites

System Composition: Continuous Clean Room Monitoring Systems and Continuous Pressure Monitoring Systems

Temperature, Humidity, Particle Count, and Pressure – Units inside the Clean Room

System keeps the clean room in compliance and sends out alerts if any degradations occur.

Integrated web-based reporting system

Readings by each Unit

Trends & thresholds by date range
Situational Awareness

- Asset Location
- Dwell Time & Utilization
- Point of use Deliveries
- Automated Transactions

Indoor RFID Infrastructure

Outdoor Flight Line Asset Tracking

Automated Receipt Transactions

Passive RFID Reader
Boeing Research & Technology is focusing on path monitoring with alerts that enable safe autonomous AGV operation in manufacturing areas. This effort will avoid possible injuries and property damage, eliminating the current practice of spotters/mechanics following the AGV as a precaution. This system is currently targeted for Composite small parts movements from lay-up fabrication area to autoclave and will be replicated toward similar use cases.
Confined Space Communication & Air Quality Detection

Current Process
1. Radio checkout & registration
2. Location, Scan a flag
3. Chemicals in work area
4. Radio place in stand-by mode
5. In workplace radio placed in active mode
6. Communication with command center
7. Radio check-in upon completion

New Process

Communication System for Confined Space Areas (CSCAH) Command Center

Registration
BEMS ID, Supervisor Name

Enter Chemicals, Location

Check our Two-Way Radio

Optional MX-4 Gas Sensors Used by Mechanics

EHS Air Monitoring Equipment

Configurations Monitor Console

Location Detection: Device Location + Beacon Beacon

Beacon

Base station

Interface controller

3-in-1 Personal Safety Device

ACSMS Backend server

Command Centre

Monitoring Console
Fall Protection Safety System

• System detects if a person working on stackers is attached to a self retracting lifeline cable.
• Alerts to the operator if an unsafe condition is suspected
• Intrusive toward the painters but the system cannot be easily turned off
• Meets all Fire and Safety Standards
Implementation Roadmap for Physical Systems

- **Design Plan**
- **Network Infrastructure**
  - Network Drops; Capacity; Interoperability
  - Equipment Installation
- **Construction & Networking Contractors + IT Systems**
- **Equipment Supplier**
- **Digital Thread**

Requirements for 110V power connection and Ethernet drop connection:
- Work Stools and Capital Equipment
- Talk/Heartbeat/Presence Sensors
- Parking/Exit Sensors
- Digital Posters
- Network Cameras
- UHF (Ultra High Frequency) RFID
- UV Sensors

Data Integration