ENTERPRISE INTEGRATED HEALTH MANAGEMENT SYSTEMS FOR RELIABLE SUSTAINMENT, MAINTENANCE AND LIFECYCLE MANAGEMENT

22nd Annual Systems and Mission Engineering Conference - October 2019
• $1.25B global software company, headquartered in Boston, MA
  – Innovation Platform: IOT & AR/VR
  – Digital Twin Solutions: CAD & PLM
• 28,000 active customers
• 6,000 employees
• Strategic technology partner to world-leading manufacturing companies
• NASDAQ:PTC - market cap ~$10B
CONVERGENCE HAS SHAPED OUR IDENTITY

PHYSICAL WORLD

Innovation Platform

IoT & Analytics   | 🔄 thingworx®
AR/VR          | 🔄 vuforia®
Industrial Connectivity | 🔄 kepware®

$1B technology investment connects to the PHYSICAL world

“PLM”

30 year heritage in the DIGITAL definition, software, and lifecycle management of things

“IoT”

PLM Solutions

CAD       | 🔄 creo®
PLM   | 🔄 windchill®
ALM    | 🔄 integrity®
SLM    | 🔄 servigistics®

DIGITAL WORLD
PTC PRODUCTS ARE WIDELY USED ACROSS FA&D

ARMY

NAVY

NASA

US DoE

A&D

FED
RELIABLE SUSTAINMENT & LIFECYCLE MANAGEMENT CHALLENGE

- Operational Availability
- Mission Reliability
- Logistics Response Time
- Total Lifecycle Cost per Unit of Usage
- Cost per Unit Usage
- Logistics Footprint

DOD DIGITAL ENGINEERING STRATEGY
JULY, 2018

- Infrastructure - robust, enabling, organized
- Data - accessible, real-time, accurate
- Extensibility - flexible & adaptive vs rigid
- Standards - common reference vs closed
- Innovation - systemic vs ad-hoc
- Perspective - solution level; process aware
Performance Based Logistics (PBL)
- U.S. DoD Strategy (1998-2014)
- Implemented in U.S. military and DoD network
- PBL 3 Levels of Implementation:
  - Condition-based Maintenance (CBM)
  - Reliability-centered Maintenance (RCM)
    - L&MR – Supply chain SCOR model
    - Immediate, Deferred, Scheduled, Preventative
    - Data Analytics & Decision Support (CBM+)
  - Enterprise Assets Management (EAM) and Service Parts Management (SPM)
    - In-Service Parts Management
    - Inventory management, optimization and forecasting
  - Integrated system health management (ISHM/IVHM)
    - Asset Performance Management (APM)
    - Health and usage monitoring systems (HUMS)
TIME-BASED OR USAGE-BASED MAINTENANCE CHALLENGE

Depot Operations, Overhaul and Manufacturing

CBM+ in the U.S. DoD:

MRO Network and Supply Chain:

• Time Based Maintenance (TBM) (Immediate, Deferred, Scheduled, Planned, Periodic)

• Time Based Condition Assessment (TBCA) - ISO 13374 – Machine Conditions Assessments

• Preventive Maintenance (PM) – part of RCM

• Risk Based Maintenance (RBM)

• Repair/Corrective Maintenance


Field Maintenance & Field Service Operations

PBL  Quality  Safety

Availability & Reliability KPIs
Preventative Maintenance - “THE PROBLEM OF OVER-MAINTAINING”

- **40%** of scheduled maintenance costs are spent on assets with negligible effect on uptime failure.
- **30%** of maintenance activities are carried out too frequently.
- **45%** of all maintenance efforts are ineffective.

only **18%** of assets have an age related failure pattern.

and **82%** of asset failures appear random.

[1] Source: [Reference 1]
[2] Source: [Reference 2]
[3] Source: [Reference 3]
INNOVATION AND MODERNIZATION APPROACH:

Digital Thread Connectedness
IIOT PLATFORM CONNECTEDNESS ENABLES:

**Maintenance Production Execution**
- Digital assembly & maintenance instructions (AR)
- Unified operator screen
- As maintained Digital Twin
- Labor tracking & shift management
- Digital interactive Illustrated Parts Catalog
- Interactive job Cards with Text to speech (AR)
- Tools tracking and monitoring
- Smart tools
- **Real time production monitoring**
  - Augmented workspace management
  - Paperless operations
  - Remote expert guidance and assistance
  - Knowledge management

**Maintenance planning and optimization**
- Maintenance and service workflow management
- Visualization, Dashboarding and sequencing of maintenance activities
- Maintenance performance KPIs and analysis
- Condition-based maintenance planning
- Service parts utilization planning
- **Asset tracking**
  - Digital repair & service instructions (AR)

**Environment, Health, & Safety**
- Health, safety, & training procedures (AR)
- Automatic inspections (AR)
- Zone inspections (AR)
- **Flexible & adaptable workforce**
- Energy management

**Asset health and performance monitoring**
- Real time alert & fault identification
- Asset trending & troubleshooting
- Monitor operating conditions to alert of anomaly or risk
  - Condition-based, Predictive & prescriptive analytics (multiple assets/fleet)
  - Deferred defects tracking and monitoring
  - Asset condition dashboard
  - Advanced algorithms for failure prediction
  - Airframe structural damage detection and analysis

**Retrofit - Major/Minor Changes**
- BOM transformation
- Digital process planning and workflow
- 3D work instruction Authoring (AR)

**Quality & Test**
- Real-time quality KPIs
- Zone quality inspections (AR)
- Robotic inspection monitoring
- Testing monitoring & calibration

**Supply chain and Logistics (SPM)**
- Inventory management and tracking
- Inventory levels optimization, demand forecasting
- Materials handling, tracking and availability
- Spare Parts Management (SPM), Life Limited Parts Management (LLP), Parts Catalogs
- Supplier management and visibility

**Ubiquitous machine & device connectivity**
- Sensor & IoT gateway connectivity
- Secure access to industrial operations data
- OPC server monitoring
- M2M advanced tags

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PTC
CONDITION-BASED AND PREDICTIVE MAINTENANCE

Maintenance performed based on evidence of need (only when it is needed)

Real-time operational data for anomalies or undesirable trends integrated with RCM (Preventative) analysis

- Condition Monitoring using sensors
- Assets/Tools Health Monitoring
- Prognostic Fault and Failure Prediction
- Data Analytics and AI for Prescriptive Maintenance
- Integration of Preventative Maintenance Methods, LM&R and PBL
- Integration of Service Parts and Supply Chain Management

Interoperability between:
- MIS - Maintenance Information Systems
- Enterprise Assets Management (EAM) Systems
- Reliability, Quality, FRACAS and Risk Mgt. systems
- Depot, Repair and Stock
- Warehouse, Warranty and Freight Systems
- Procurement, Order, Financial and ERP Systems
- PLM Systems for E-BOM, M-BOM and In-Service BOM management

CBM+ 4.0
CBM + 4.0 BUILDING BLOCKS

SPM
- Supply Planning
- Inventory Optimization
- Demand Forecasting

Connected SPM
- LLP Forecasting
- Failure Prediction

IIOT Analytics
- Machine Learning

AR Service Execution
- Real-time IoT Service Data

IIOT Platform (ThingWorx)

Data Sources and Enterprise Systems of Record
- PLM / ERP / MRO Maintenance Information System
- Asset Management Systems (EAM)
  (In-Service Config / SBOM, Maintenance planning, maintenance execution)
- ERP, finance, CRM, Procurement, Depots, Portals, contracts

Condition Monitoring Dashboards
- Failure Prediction, What-If Analysis, KPIs
- Procurement, Repair & Transfer Recommendations and triggering
DIGITAL TRANSFORMATION THROUGH CBM+ 4.0

**ThingWorx IIOT Platform**
- Seamless connectivity between the systems

**Service Parts Management (SPM):**
- Supply-chain planning
- Availability based Inventory Optimization
- Demand Forecasting

**Connected Service Parts Management (C-SPM):**
- Proactive assets and parts utilization planning
- Failure prediction

**Vuforia AR**
- Interactive AR based work instructions

**Real-time data and Digital Twin systems engineering approach**

**PRODUCTS**
- Prognostic service and maintenance monitoring of assets deployed in the field
- Life-limited spare parts management and SPM forecasting
- Inventory and operations optimization based on demand forecasting - connected maintenance
- Asset tracking, trending & troubleshooting

**PEOPLE**
- Health, safety, & training procedures with Augmented Reality (AR)
- Interactive 3D Digital repair & service instructions with Augmented Reality (AR)
- Remote assistance

**PROCESSES**
- Real time triggering of maintenance events
- Energy and supply optimization for the shop floor
- Release to service digital workflow
- Real time maintenance production monitoring
ON ASSET MAINTENANCE - INTEGRATION SCENARIO

**ThingWorx IIOT Platform**
- Seamless connectivity between the systems

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- Supply-chain planning
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- Proactive assets and parts utilization planning
- Failure prediction

**Vuforia AR**
- Interactive AR based work instructions

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**Fully Integrated through connected systems workflow process**

- **DOD Supply Chain operations reference model (SCOR)**

- **Plan**
- **Source**
- **Make/Repair**
- **Deliver**
- **Return**
- **Operate**
- **Understand**
ON ASSET MAINTENANCE - INTEGRATION SCENARIO

Fully Integrated through connected systems workflow process

- DOD Supply Chain operations reference model (SCOR)

Plan | Source | Make/Repair | Deliver | Return | Operate | Understand

Start
- Monitor asset health
- Investigate failure condition
- Schedule Maintenance Activity
- Plan parts availability
- Execute maintenance on Asset
- Perform part replacement
- Update As Maintained
- Analyze consumption rates, failure rates

End
CONDITION-BASED MONITORING FOR PREVENTATIVE AND PREDICTIVE MAINTENANCE

- **Lowering costs**: 41.6%
- **Improving productivity**: 38.1%
- **Improving business process**: 28.5%
- **Accuracy**: 91%
- **Predicting alarms 24 hours in advance**: 35%
- **Unnecessary Parts Exchanges**: 10%-20%
- **Savings from Inventory Optimization**:

**PBL KPIs:**

- **20%**
  - FTFR
- **10%**
  - Asset Uptime
- **52%**
  - MTTR
REMOTE MONITORING BENEFITS...

...to ENTERPRISE
- Increase company profit
- Achieve sustainable competitive advantage

...to SERVICE ORGANIZATION
- Understand your equipment performance
- Improve first-time fix rates
- Reduce onsite service visits
- Increase service profitability

...to CUSTOMER
- Improve product and service outcomes
- Increase equipment uptime
- Increased customer satisfaction

20% Improvement in equipment uptime

15-25% Reduction in onsite service visits

5-20% Improvement on first time fix rate
PTC’s Solution Framework in MRO Sector

<table>
<thead>
<tr>
<th>3D Platform</th>
<th>Product Lifecycle Platform</th>
<th>Industrial Orchestration Platform</th>
<th>Experience Platform</th>
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</thead>
<tbody>
<tr>
<td>Associative 3D Modeling</td>
<td>Requirements Management</td>
<td>IT &amp; OT Data Acquisition</td>
<td>Object Recognition &amp; Tracking</td>
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<tr>
<td>Generative Design</td>
<td>Content Management</td>
<td>Contextualization</td>
<td>Spatial Recognition &amp; Tracking</td>
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<tr>
<td>IOT-Connected 3D Digital Twin</td>
<td>Project Collaboration, Governance &amp; Workflow</td>
<td>Data Analytics &amp; Visualization</td>
<td>Experience Authoring</td>
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<tr>
<td>3D Work Instructions</td>
<td>BOM Management</td>
<td>Business Process Flow</td>
<td>Expertise Capture</td>
</tr>
<tr>
<td>Configured Digital Mockup</td>
<td>Change &amp; Configuration Management/Digital Thread</td>
<td>UX Composition</td>
<td>Logical Procedure Guidance</td>
</tr>
<tr>
<td>3D Spatial &amp; Object Capture</td>
<td>Product Variability Management</td>
<td>Domain-specific Logic Composition</td>
<td>Ad Hoc Collaborative Experiences</td>
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<tr>
<td>Design for Additive Manufacturing</td>
<td>Manufacturing Process Management</td>
<td>Domain-specific Data Models Composition</td>
<td>HMI / Experience of Things</td>
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<tr>
<td>Multi-CAD Collaboration</td>
<td>Service Process Management</td>
<td>Industrial Protocol Translation</td>
<td>Multi-Platform Device Support</td>
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<tr>
<td>Real-time Simulation</td>
<td>Quality Management</td>
<td>Digital Content Management &amp; Remote Access</td>
<td>Content Management</td>
</tr>
</tbody>
</table>

**Logos:**
- creo®
- windchill®
- thingworx®
- vuforia®
CBM + CASE STUDIES
THE "END GAME" SCENARIO FOR IOT BASED MAINTENANCE

Integrating Systems to Life Management Processes

Alerting
2) ThingWorx application monitors sensor data and confirms that problem or other conditions exist that trigger maintenance

Diagnostics
3) Diagnostics rules and maintenance schedules are used to identify or predict maintenance needs

Supply, Provisioning
4) Required parts are identified or ordered via optimal supply location, owner, utilization, condition.

Work-order Automation
5) Work Order generated in the maintenance systems with parts status for technician scheduling

Data Capture
1) Sensor data gathered from connected asset inside depot

Asset Restored
7) Service is performed, restoring asset to proper condition

Technical Data Integration
6) Required technical data and instructions are located and attached to work order
UAV ENGINE HEALTH MONITORING AND ANALYSIS

Assets health monitoring, fault and failure prediction

- Sensor data captured and gathered from equipment on board in various modes:
  - In-flight mission
  - Pre-flight mission readiness tests
  - Take-offs and landings
  - Etc..
- Data log files downloaded in the depot after mission and uploaded into ThingWorx-based CBM system
- Predictive models have been built in ThingWorx, based on analysis of:
  - 500 flight with 18 critical equipment failures

Objective: failure alerts/alarms 48-24 hours prior actual equipment failure
This document does not contain U.S. export controlled technical data.
Every second of every day, over 69 Predator-series aircraft are airborne worldwide.

5.5 Million total flight hours
2018 - Over 600,000 flight hours
OSH KOSH DEFENSE DEMO STORYBOARD – CBM THREAD

1. **Warfighter/Maintainer**

   **AR-Enabled Condition-Based Maintenance**
   - **WARFIGHTER**: Condition-based maintenance performed by the field operator (warfighter) based on sensor data combining scheduled and planned maintenance with predictive maintenance.
   - **MAINTAINER**: Preventative Maintenance procedures in the depot (Wheel End, Brakes, Damage Repair)

2. **Connected Fleet Management**

   **SERVICE OPERATION MANAGER**: Depot-driven maintenance – see the vehicles in the depot. Estimate when all the vehicles will be repaired – Scheduled and planned procedures – order spare parts based on planned & scheduled maintenance (SPM).

   **QUALITY & RELIABILITY MANAGER**: Analyze based on Quality and Risk across fleet - initiate ECR/ECN initiates generative design

3. **Generative AI Redesign & Review**

   **DESIGN ENGINEER**: Digital Twin-driven design investigation and change. Change is justified by the risk analysis. ECR is created with justification

4. **AR-Enabled Work Instruction**

   **ASSEMBLER**: Choose from multiple truck configurations which impact the Roxtec wire config

   **Parts List**
   - Visualize new suspension design with analysis results
   - Visualize JLTV Variant designs in AR (other design variants)

**Notes**:
- Cast
- Formed
- 3D Print
**POST-MISSION INSPECTION EXPERIENCE**

1. **NOTE AIR RESTRICTION IS GREEN, WARNING ICON IS GONE, MISSION CAPABLE AUTO CHECKED**

### Verify Vehicle Operation

<table>
<thead>
<tr>
<th>Vehicle Operation</th>
<th>Mission Capable</th>
<th>Not Mission Capable</th>
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<tbody>
<tr>
<td>Oil Pressure</td>
<td>18 psi</td>
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<tr>
<td>Idle Speed</td>
<td>827 RPM</td>
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<tr>
<td>Water Temp</td>
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<tr>
<td>Voltage</td>
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<tr>
<td>Terrain Setting</td>
<td>Highway</td>
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<tr>
<td>Tire Pressure 1</td>
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<tr>
<td>Tire Pressure 2</td>
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<tr>
<td>Tire Pressure 3</td>
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<tr>
<td>Tire Pressure 4</td>
<td>149 psi</td>
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<tr>
<td>Air Restriction</td>
<td>43 in-H2O</td>
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<tr>
<td>Engine Coolant</td>
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<tr>
<td>Transmission Oil</td>
<td>439 deg F</td>
<td></td>
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<tr>
<td>Susp. Autolevel</td>
<td>Enabled</td>
<td></td>
</tr>
</tbody>
</table>
Creating and orchestrating a digital thread from internal teams and also externally to partners, suppliers and customers.

For Lufthansa Technik, the seamless integration between Windchill® and ThingWorx® will enable new levels of collaboration both internally and among many suppliers.

Windchill will serve as the engineering backbone to enable R&D and manufacturing to work concurrently. The secure data repository will also help the company protect its Intellectual Property across its global supply chain while generating greater revenue streams through new and innovative digital business models.
Created a fully connected shop floor for real-time asset health monitoring and predictive maintenance to improve quality and speed of maintenance, repair, and overhaul services.
PTC THINGWORX FOR IIOT OR RC HESTRATION PLATFORM (AIRLINE)

Repair:
Access digital product information

PLM + TWX

OTAL-787-001
Flying hours

Weather patterns

TWX

TWX Apps

AI/Machine learning platform

Airline HQ

Strain gauge sensors detect crack in wing spar bracket

TWX IoT Platform

Aircraft maintenance hangar

Should we repair or replace the portside wing spar bracket on OTAL-787-001?

Relevant information

TWX + SPM

Replace:
Initiate spare part procurement

Historical wing spar failure rates

Wing maintenance schedules

Cloud

Parts Ordering Portal

Aircraft part suppliers

Maintenance engineer

3PL

Leading Airline and MRO public information
Interoperability between:

- MIS – Maintenance Information System
- Reliability, Quality, FRACAS and Risk Mgt systems
- Depot, Repair and Stock
- Warehouse, Warranty and Freight Systems
- Procurement, Order, Financial and ERP Systems
- PLM Systems for E-BOM, M-BOM and In-Service BOM management

June 7, 2019 - Lufthansa Technik Group Embarks on Digital Transformation Journey with PTC Windchill and ThingWorx

Thank You!

David Segal
Sr. Director, Business Transformation, FA&D Industry
dsegal@ptc.com
Interactive Predictive Analytics Dashboards

FAILURE RISK ANALYSIS

Turbine ETX1234

3.7%  Portfolio Risk  3.2%

Anomaly Reports

<table>
<thead>
<tr>
<th>TIME</th>
<th>DESCRIPTION</th>
<th>REPORT</th>
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