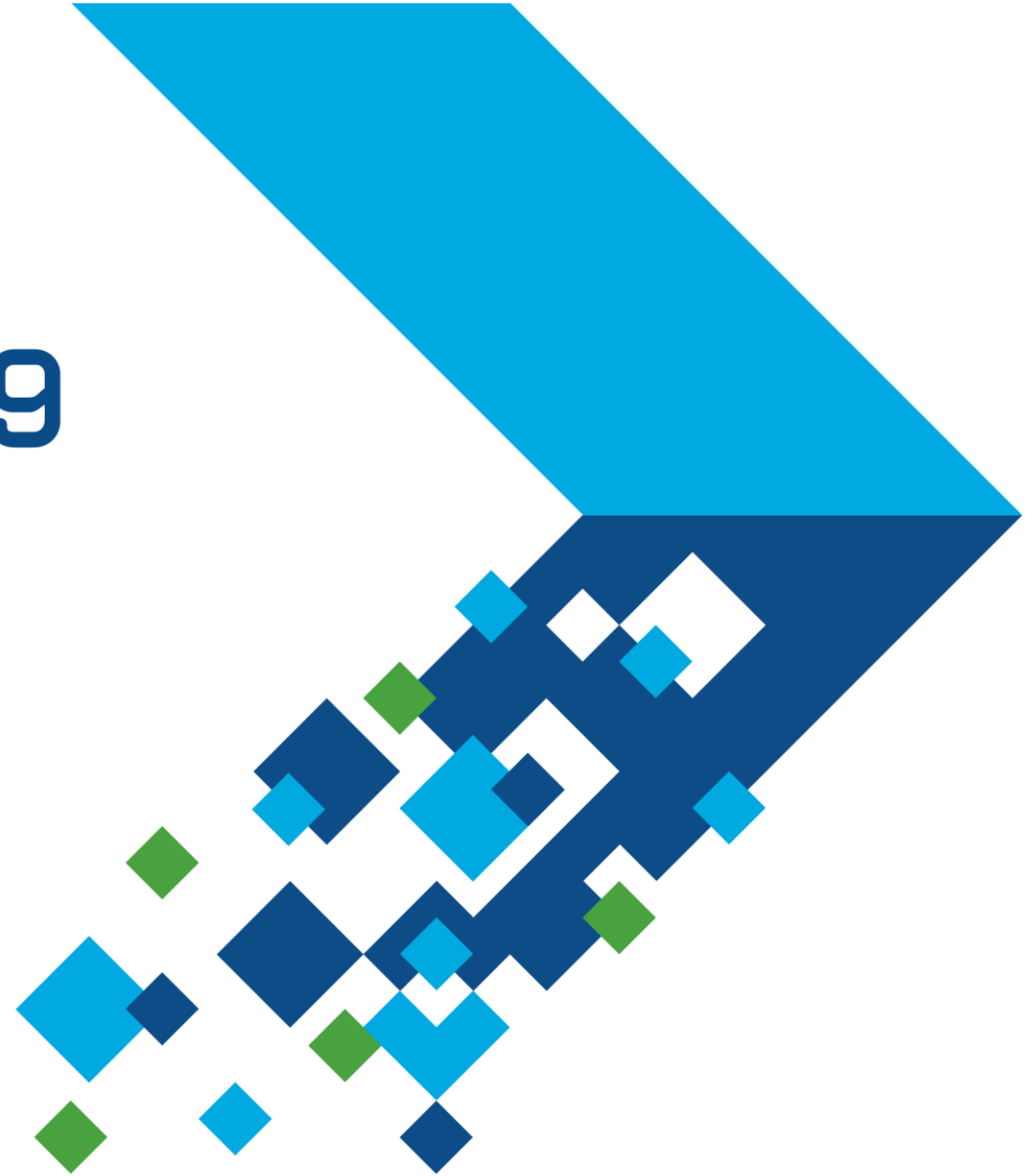


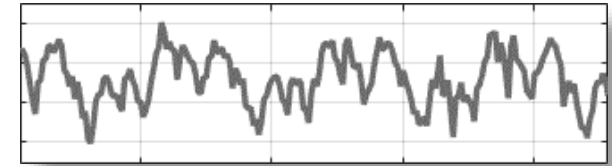
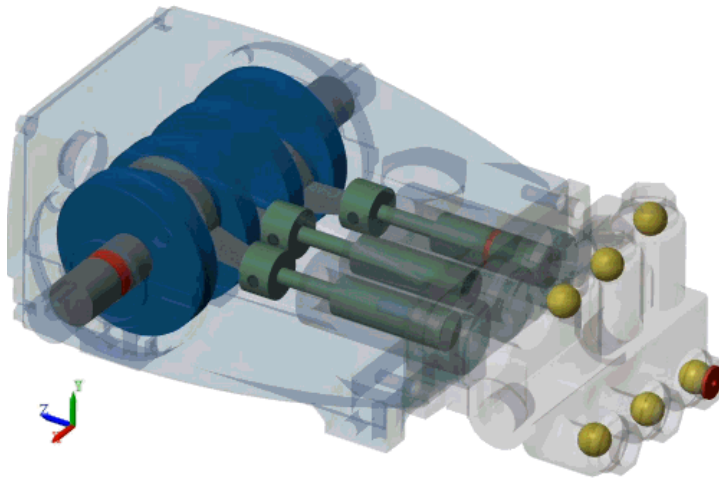
MATLAB EXPO 2019

Predictive Maintenance with MATLAB – Master Class

Antti Löytynoja, Senior Application Engineer



What is Predictive Maintenance?



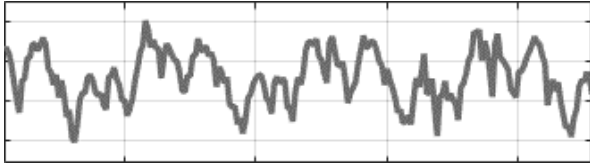


English Spanish French Pump - detected ▼



English Russian Greek ▼

Translate



1/5000

I need help.



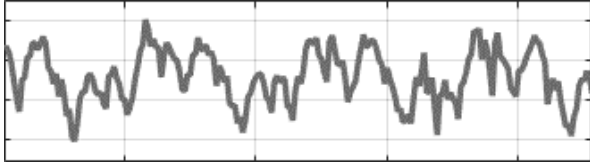


English Spanish French Pump - detected ▼



English Russian Greek ▼

Translate



1/5000

I need help. One of my cylinders is blocked. I will shut down your line in 15 hours



A Predictive Maintenance Algorithm Answers These Questions

**Is my machine
operating
normally?**

**Anomaly
Detection**

I need help.

**Why is my
machine behaving
abnormally?**

**Condition
Monitoring**

One of my cylinders is blocked.

**How much longer
can I operate my
machine ?**

**Remaining
Useful Life
Estimation**

I will shut down your line in 15 hours.

Predictive Maintenance Toolbox for Developing Algorithms

Is my machine
operating
normally?

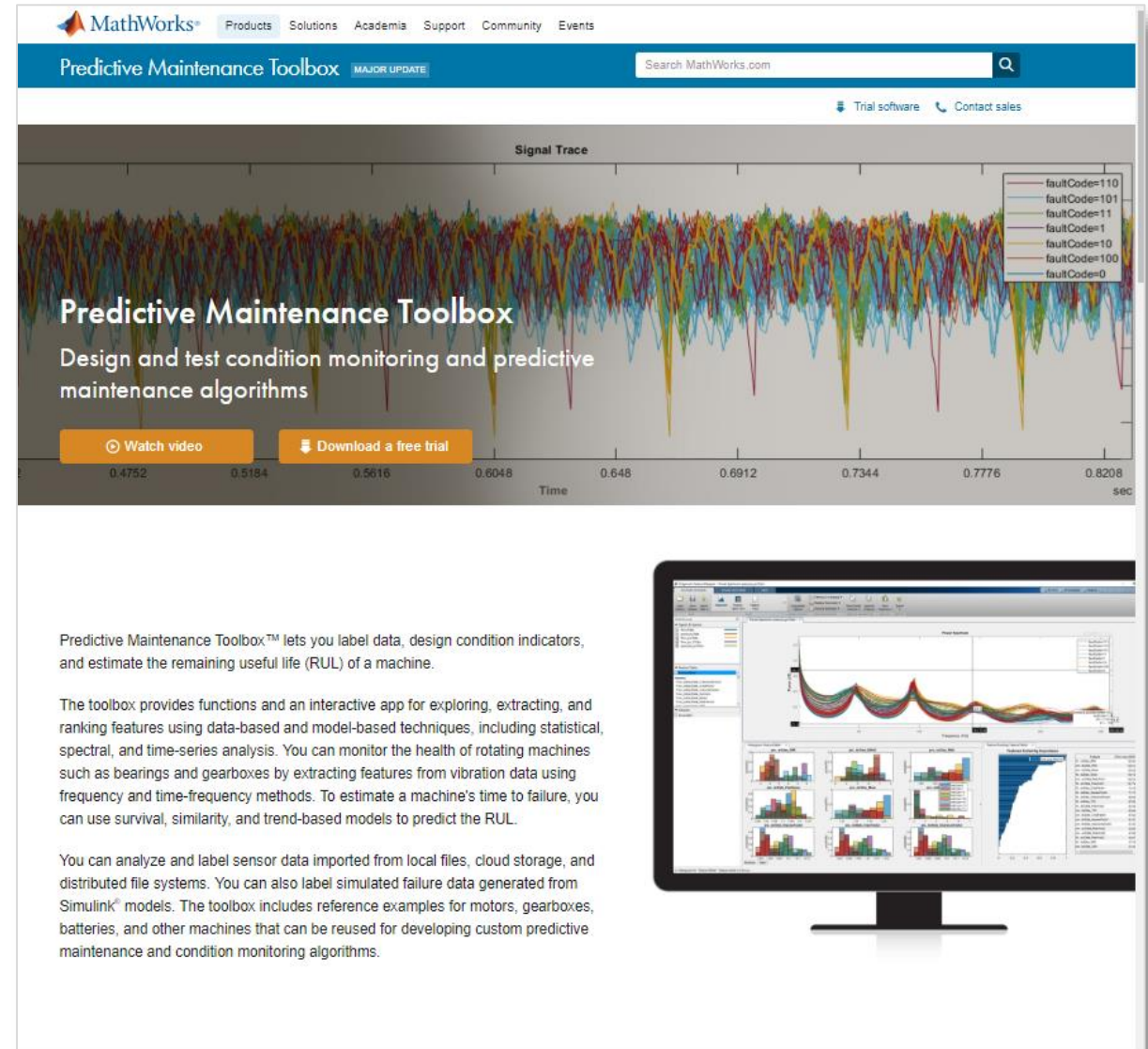
**Anomaly
Detection**

Why is my
machine behaving
abnormally?

**Condition
Monitoring**

How much longer
can I operate my
machine ?

**Remaining
Useful Life
Estimation**




The screenshot shows the MathWorks Predictive Maintenance Toolbox website. The header includes the MathWorks logo and navigation links: Products, Solutions, Academia, Support, Community, Events. Below the header is a search bar and a 'MAJOR UPDATE' badge. The main content area features a 'Signal Trace' plot with multiple colored lines representing different fault codes. The plot is titled 'Predictive Maintenance Toolbox' and 'Design and test condition monitoring and predictive maintenance algorithms'. Below the plot are two buttons: 'Watch video' and 'Download a free trial'. The x-axis is labeled 'Time' and the y-axis is labeled 'sec'. A legend on the right lists fault codes: faultCode=110, faultCode=101, faultCode=11, faultCode=1, faultCode=10, faultCode=100, and faultCode=0.

Predictive Maintenance Toolbox™ lets you label data, design condition indicators, and estimate the remaining useful life (RUL) of a machine.

The toolbox provides functions and an interactive app for exploring, extracting, and ranking features using data-based and model-based techniques, including statistical, spectral, and time-series analysis. You can monitor the health of rotating machines such as bearings and gearboxes by extracting features from vibration data using frequency and time-frequency methods. To estimate a machine's time to failure, you can use survival, similarity, and trend-based models to predict the RUL.

You can analyze and label sensor data imported from local files, cloud storage, and distributed file systems. You can also label simulated failure data generated from Simulink® models. The toolbox includes reference examples for motors, gearboxes, batteries, and other machines that can be reused for developing custom predictive maintenance and condition monitoring algorithms.

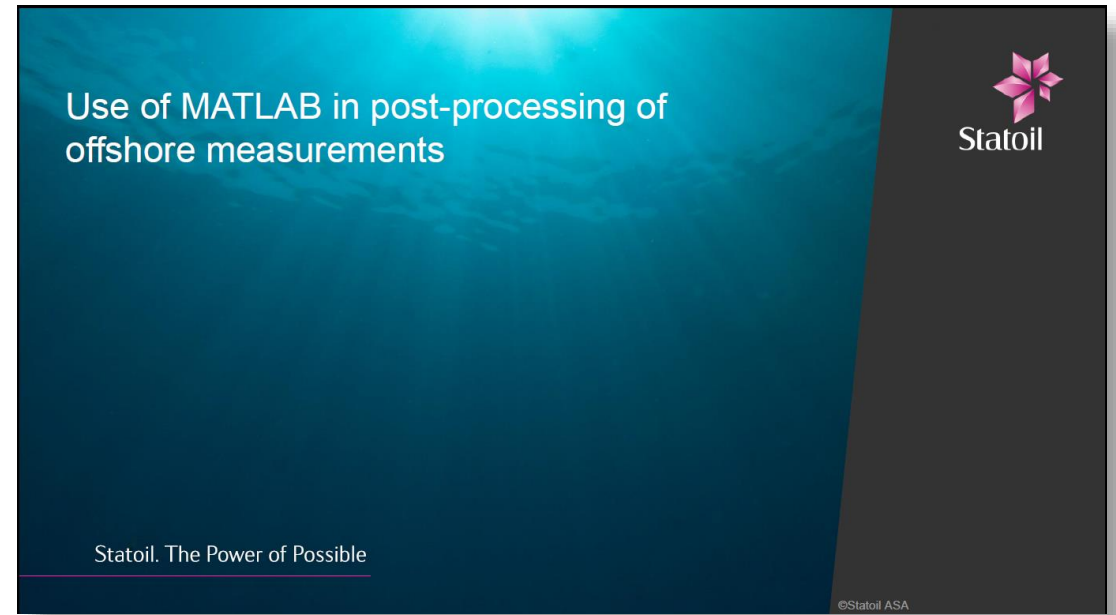


The screenshot shows the Predictive Maintenance Toolbox app interface. It displays a 'Fault Signature' plot with multiple colored lines representing different fault codes. The plot is titled 'Predictive Maintenance Toolbox' and 'Design and test condition monitoring and predictive maintenance algorithms'. Below the plot are several subplots showing 'RUL Estimation' and 'RUL Prediction'. The x-axis is labeled 'Time' and the y-axis is labeled 'sec'. A legend on the right lists fault codes: faultCode=110, faultCode=101, faultCode=11, faultCode=1, faultCode=10, faultCode=100, and faultCode=0.

How are MathWorks Tools Used for Predictive Maintenance?



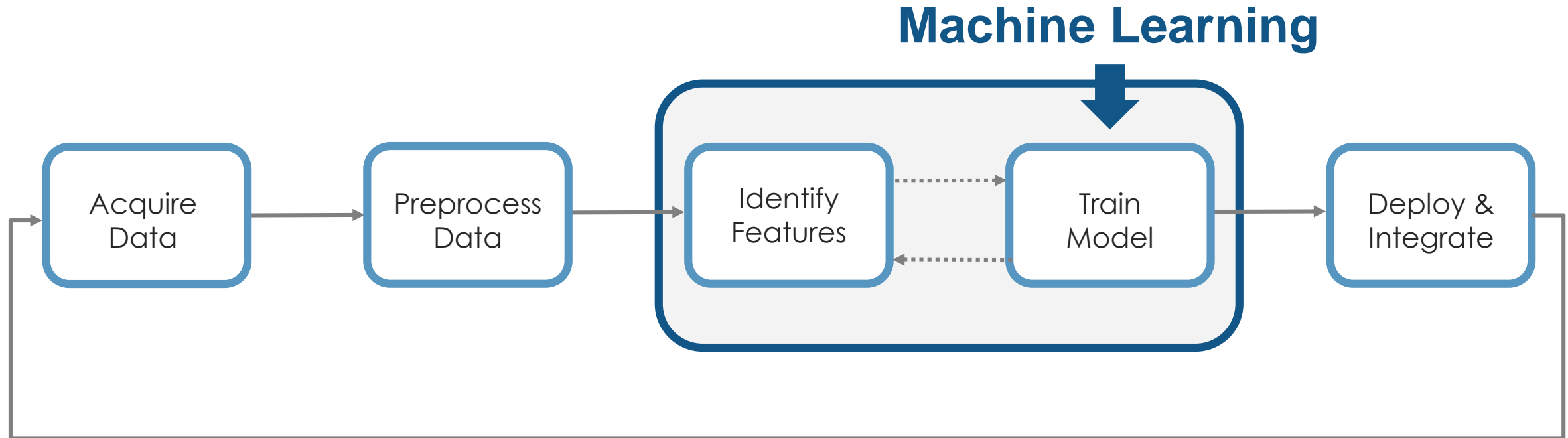
[Link to user story](#)



[Link to user story](#)



Workflow for Developing a Predictive Maintenance Algorithm

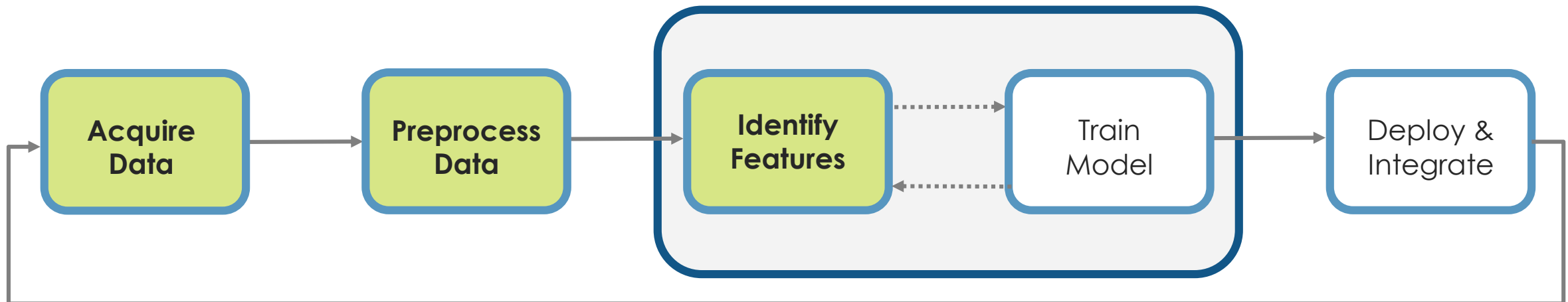


Why MATLAB & Simulink for Predictive Maintenance

- Reduce the amount of data you need to store and transmit
- Explore approaches to predictive modeling
- Deliver the results of your analytics based on your audience
- Get started quickly...especially if you are an engineer

Why MATLAB & Simulink for Predictive Maintenance

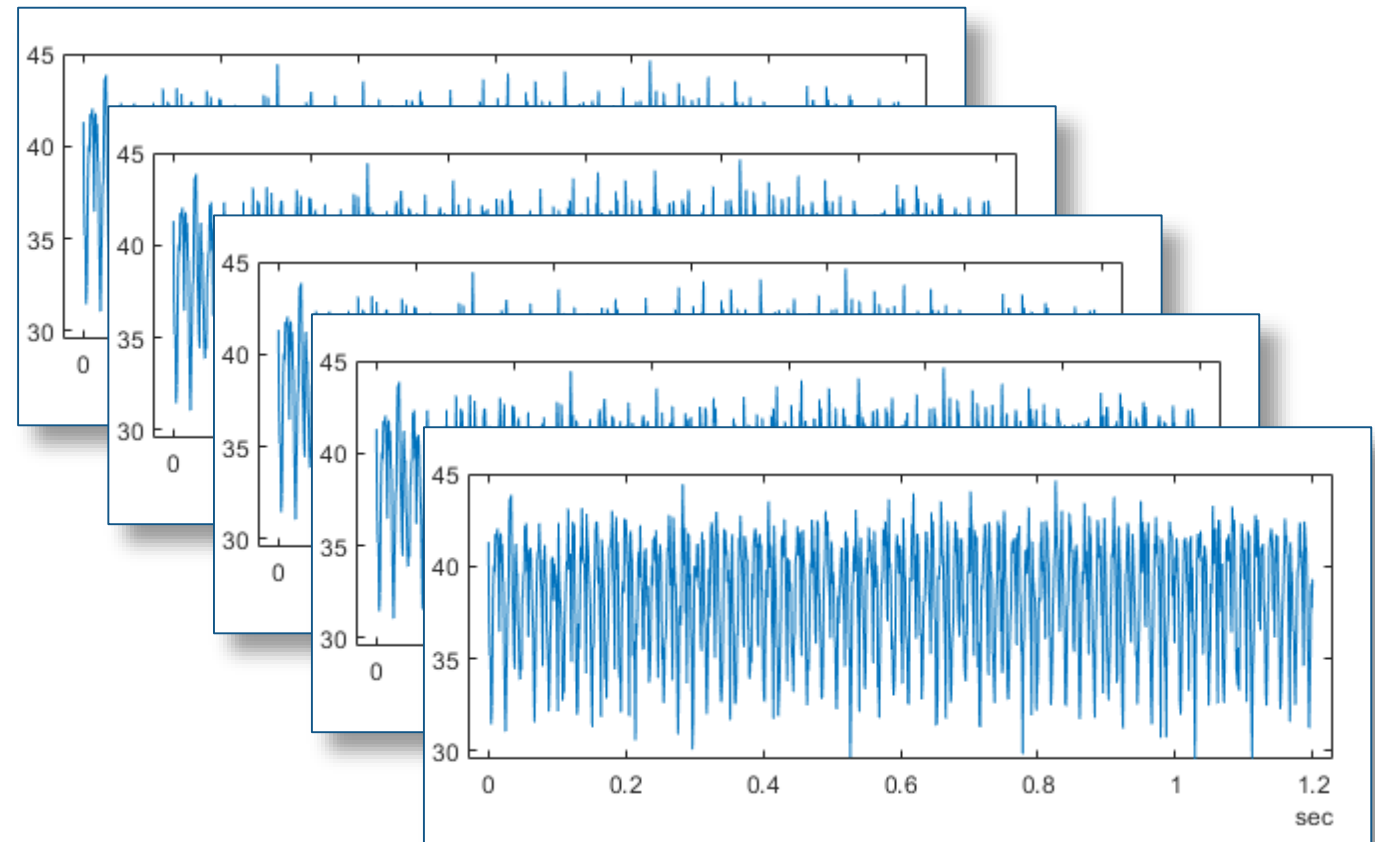
- **Reduce the amount of data you need to store and transmit**
- Explore approaches to predictive modeling
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Challenges: How do you make sense of the ALL the data being collected?

- 1 day ~ 1.3 GB
- 20 sensors/pump ~26 GB/day
- 3 pumps ~ 78 GB/day
- Satellite transmission
 - Speeds approx. 128-150 kbps,
 - Cost \$1,000/ 10GB of data
- Needle in a haystack problem

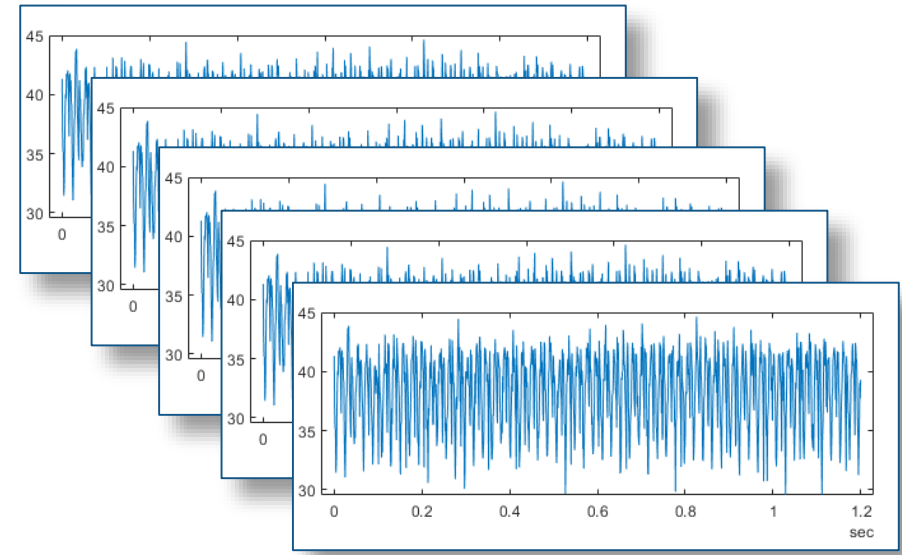
Pump flow sensor 1 sec ~ 1000 samples ~16kB



Solution: Feature Extraction

Reduce the amount of data you need to store and transmit

- How do you extract features?
 - Signal processing methods
 - Statistics & model-based methods
- Which features should you extract?
 - Depends on the application, data, and hardware
 - Requires domain-knowledge
- How do I deal with streaming data?
 - Determine buffer size
 - Extract features over a moving buffer window



qMean	qVar	qSkewness	qKurtosis
38.4945	9.2306	-0.5728	2.4662
qPeak2P...	qCrest	qRMS	qMAD
15.2351	1.1553	38.6141	2.5562

Diagnostic Feature Designer App

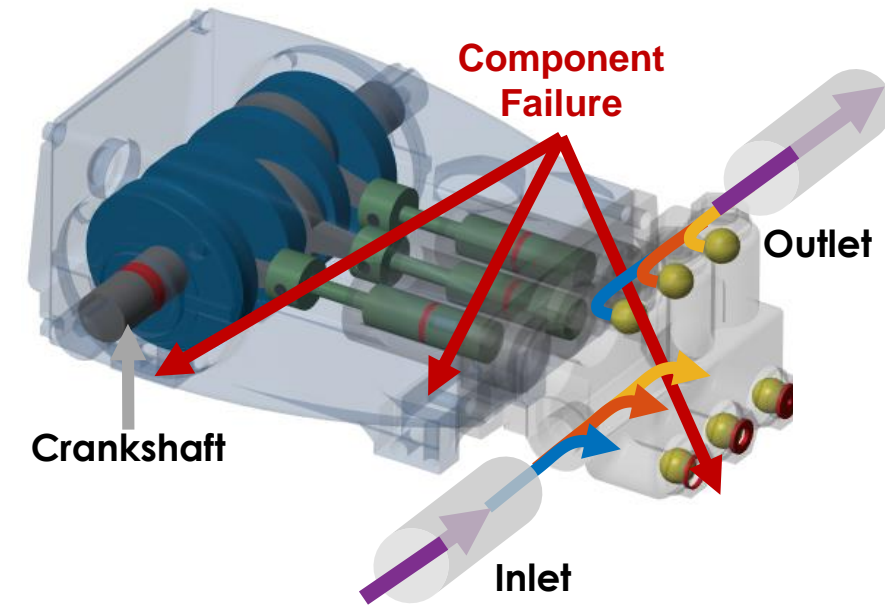
Predictive Maintenance Toolbox R2019a

- Extract, visualize, and rank features from sensor data
- Use both statistical and dynamic modeling methods
- Work with out-of-memory data
- Explore and discover techniques without writing MATLAB code



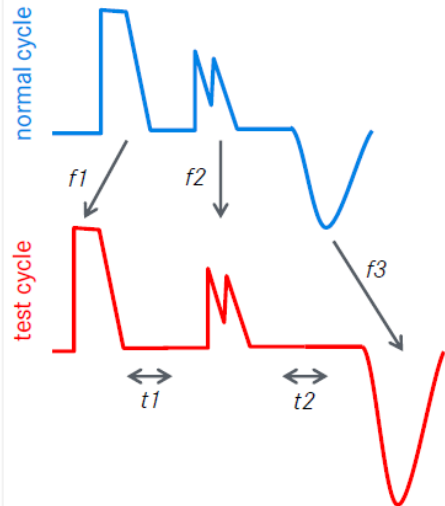
Demo: Extracting features from a signal

- Scenario: we want to monitor the condition of industrial pumps.
- Data: pressure/flow data collected from industrial pumps with different failures, 240 logs in total
- Goal: transform the sensor data into **descriptive features** that help us distinguish better the different failures and **reduce the amount of data**



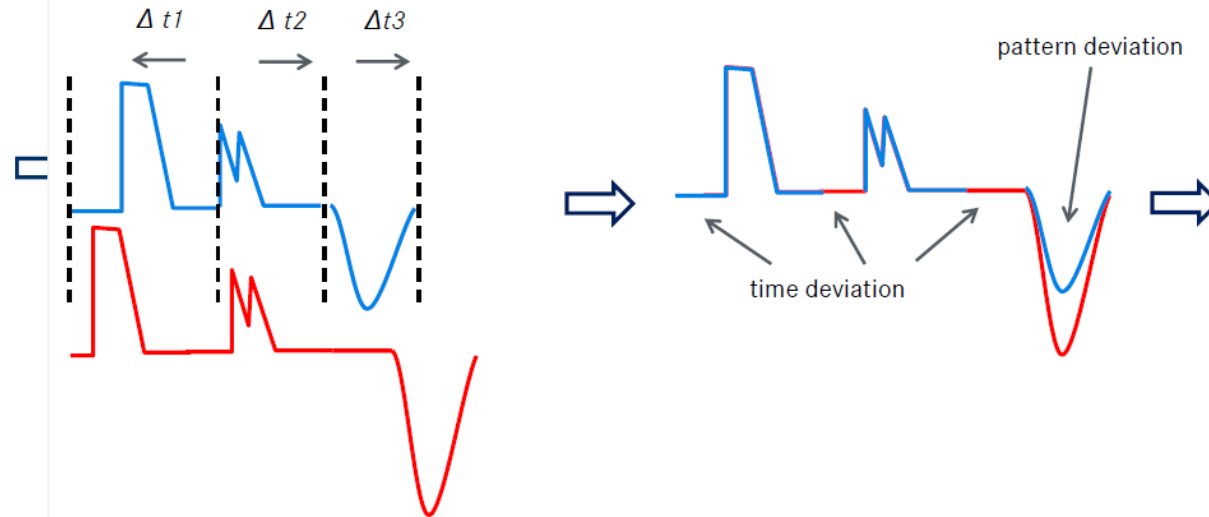
Daimler are Using MATLAB Today for Anomaly Detection

Algorithm principle



- Cycle can be described as sequence features $f1$, $f2$, $f3$
- Each cycle can show some delays in time $t1$, $t2$

Algorithm principle



- Pattern matching through shift of feature along time axis ($\Delta t1$, $\Delta t2$, $\Delta t3$): minimization of SRS

- Description of a cycle as feature sequence
- For each feature time and pattern deviation can be calculated

$f1$	$f2$	$f3$	
$\Delta t1$	$\Delta t2$	$\Delta t3$	Time deviation
No	No	Yes	Pattern deviation

- Time and pattern deviation for each feature are used as characteristic numbers for test cycle

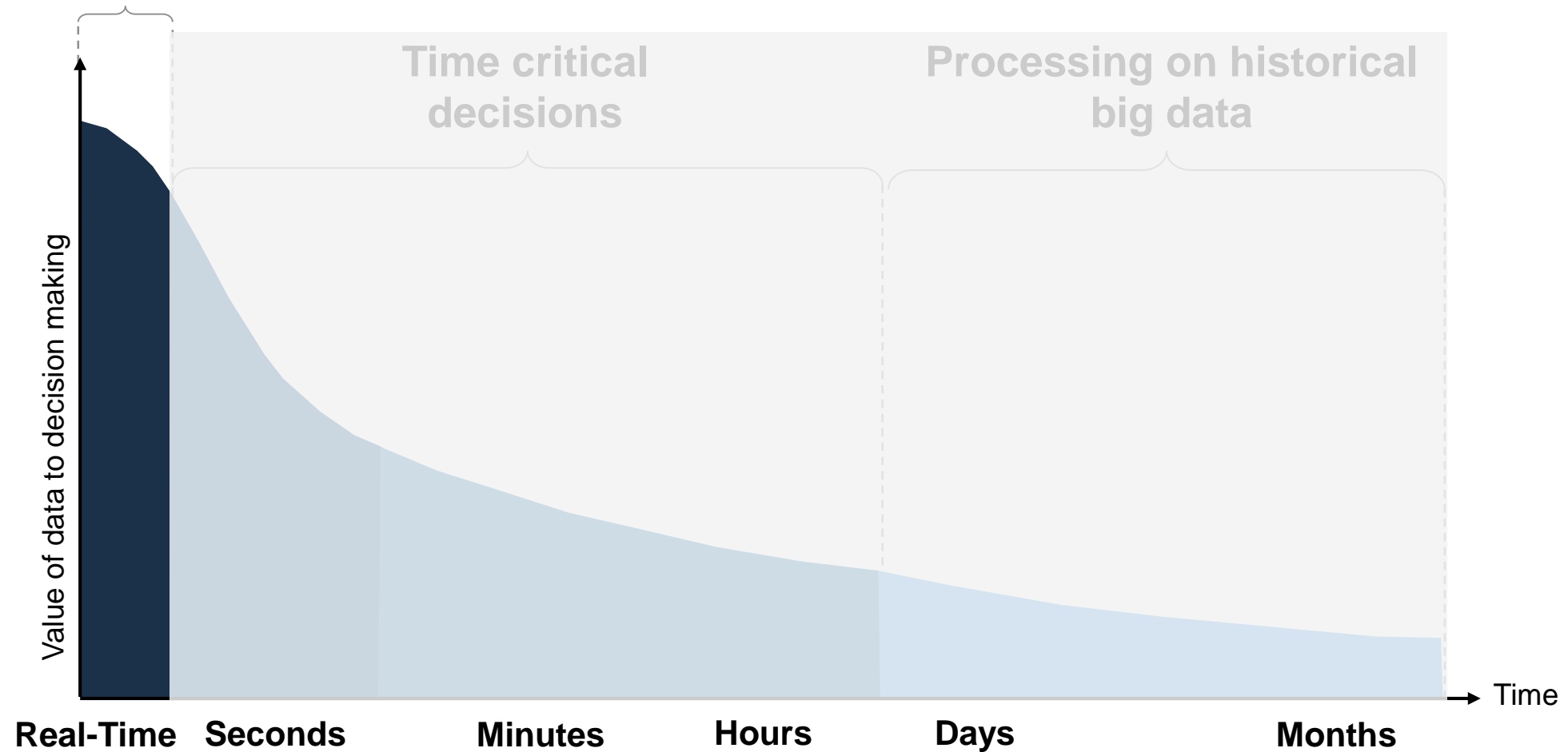


Data reduction!

Data reduction of time series by a factor of **250x** without a significant loss of information

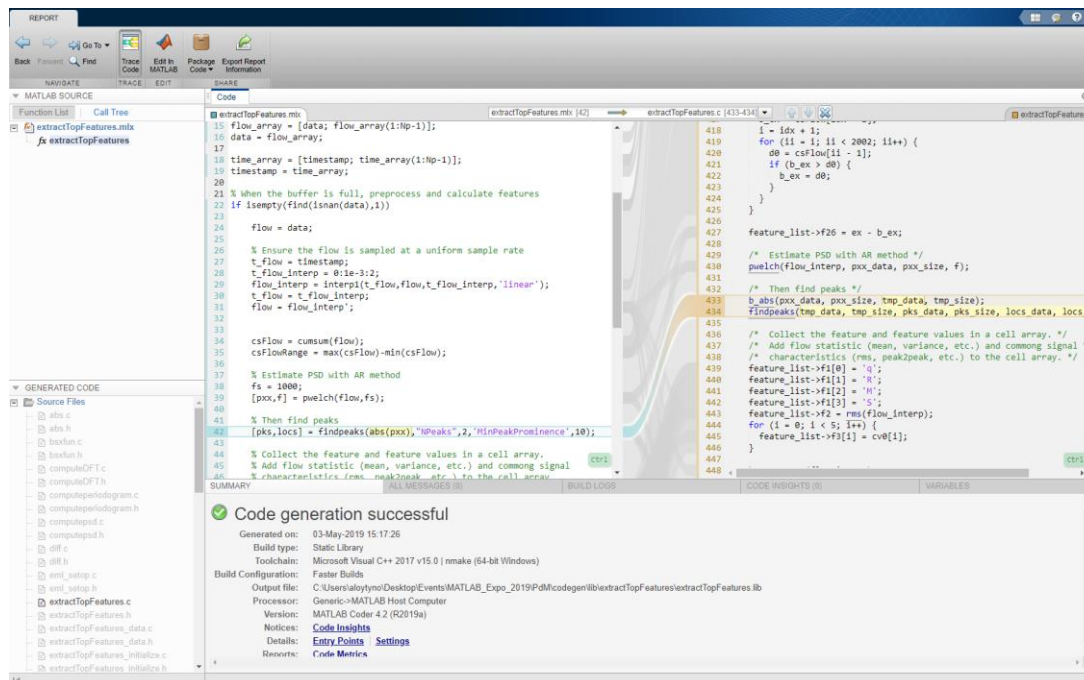
When is Your Data Most Valuable?

Near real-time decisions



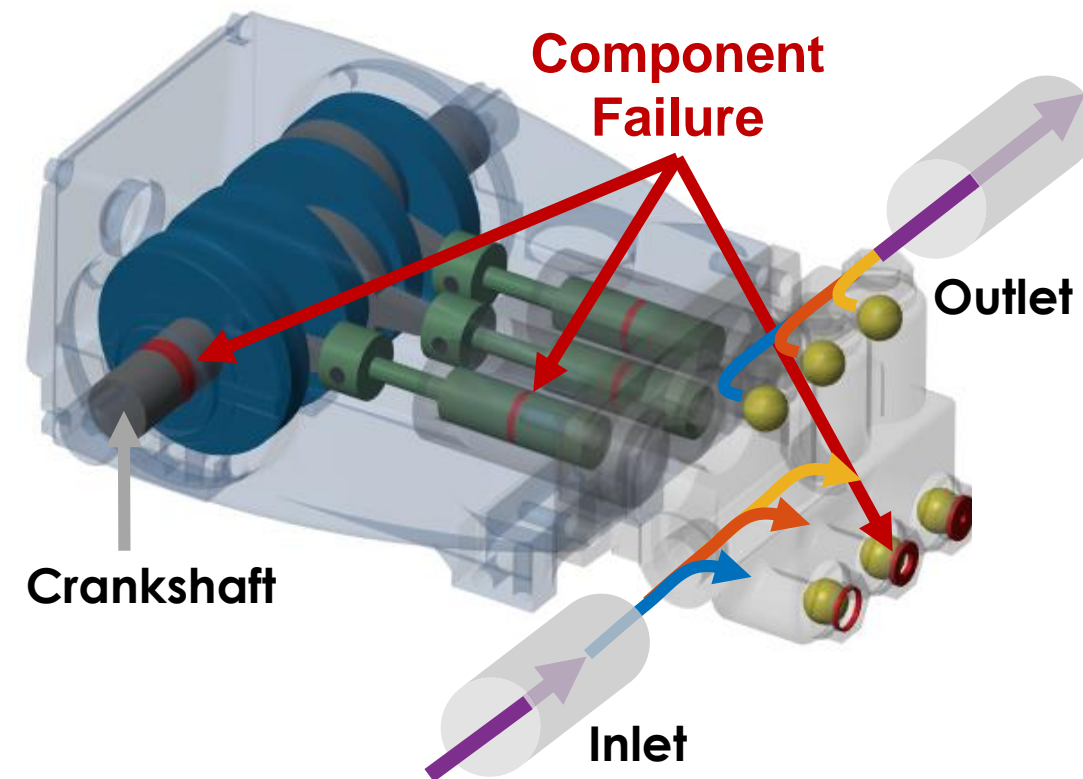
Demo: generating code for embedded systems

- Scenario: We have designed a feature extraction algorithm in MATLAB
- Goal: To implement the algorithm on an embedded system, for near-real-time processing, and to reduce the amount of data to be sent to cloud



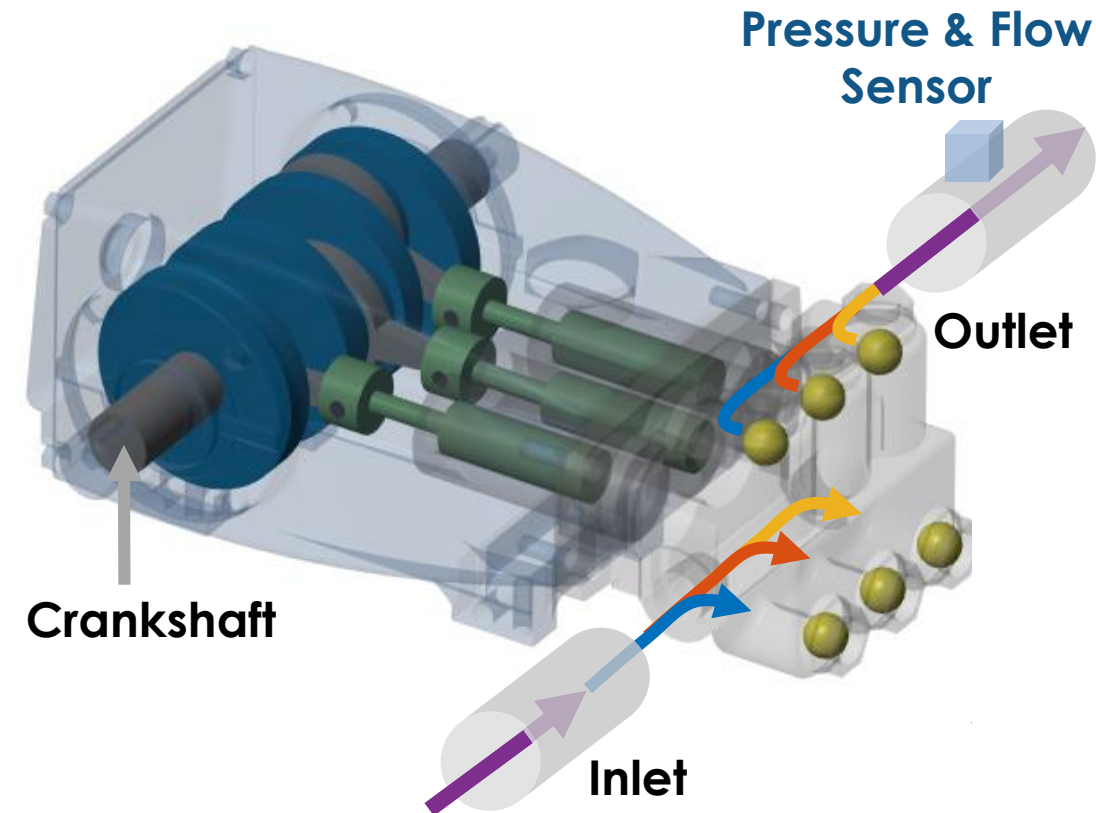
Fault Classification Algorithms Allow You to Identify the Root Cause of Anomalous Behavior

- Condition monitoring to detect:
 - Seal leak
 - Inlet blockage
 - Bearing degradation



Fault Classification Algorithms Allow You to Identify the Root Cause of Anomalous Behavior

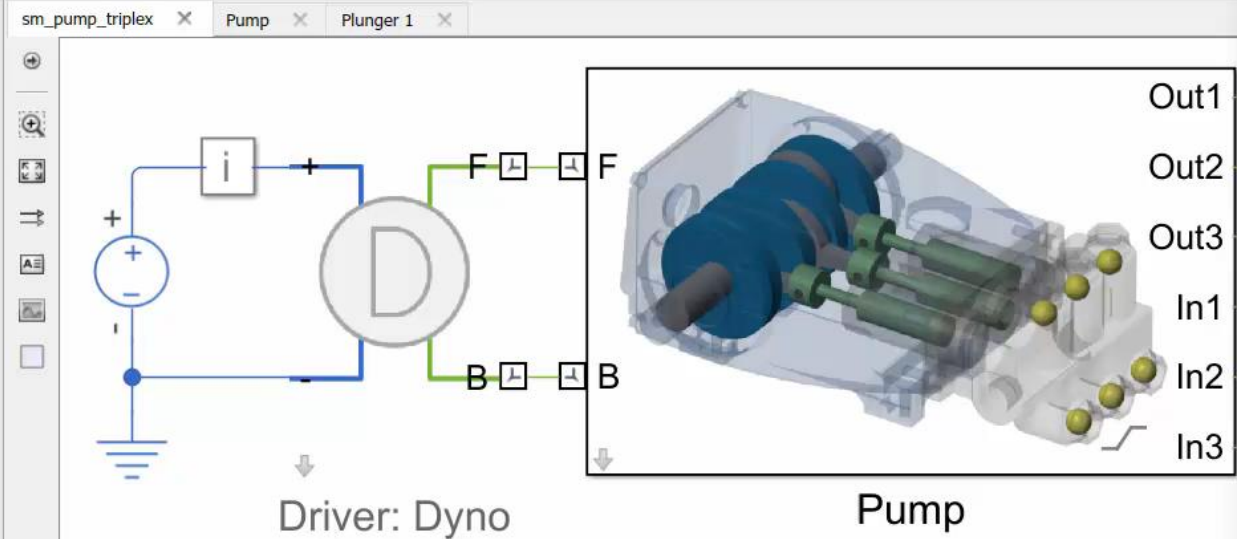
- Condition monitoring to detect:
 - Seal leak
 - Inlet blockage
 - Bearing degradation
- Identify fault present in system using **only** pressure and flow sensor data



Challenges: not enough data (or the right kind of data)!

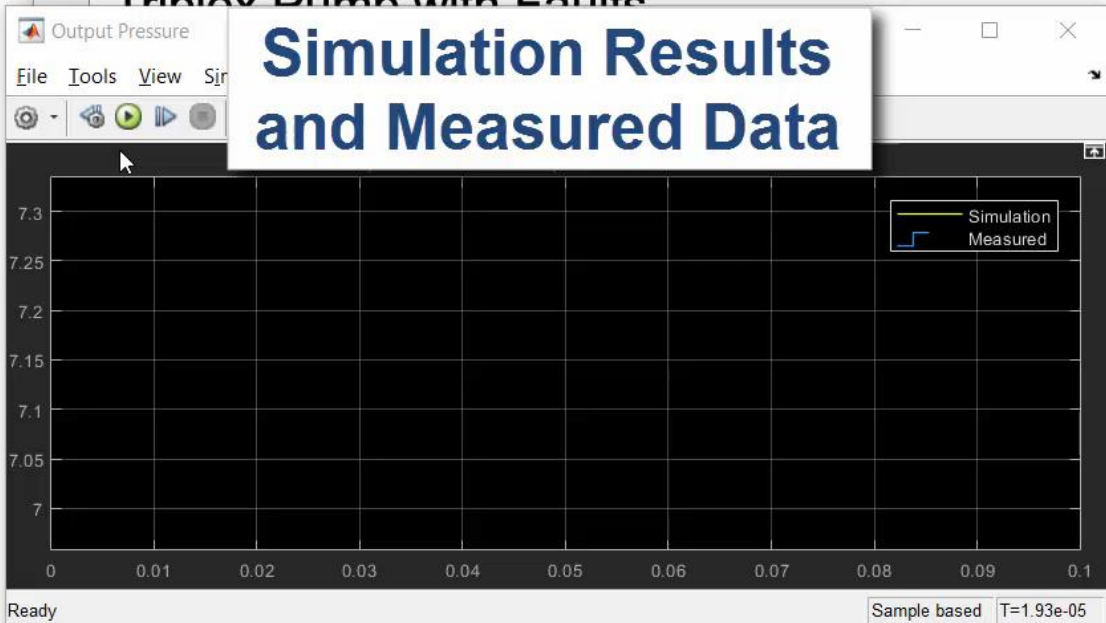
- You may have not experienced all potential failures in the equipment, or it's too costly to run real pumps into failure
- Solution: Build a digital twin of the physical machine in Simulink/Simscape, and model the failures
 - **Simscape** has blocks to model and simulate multi-domain physical systems (electrical/hydraulic/mechanical)

Simulation Model

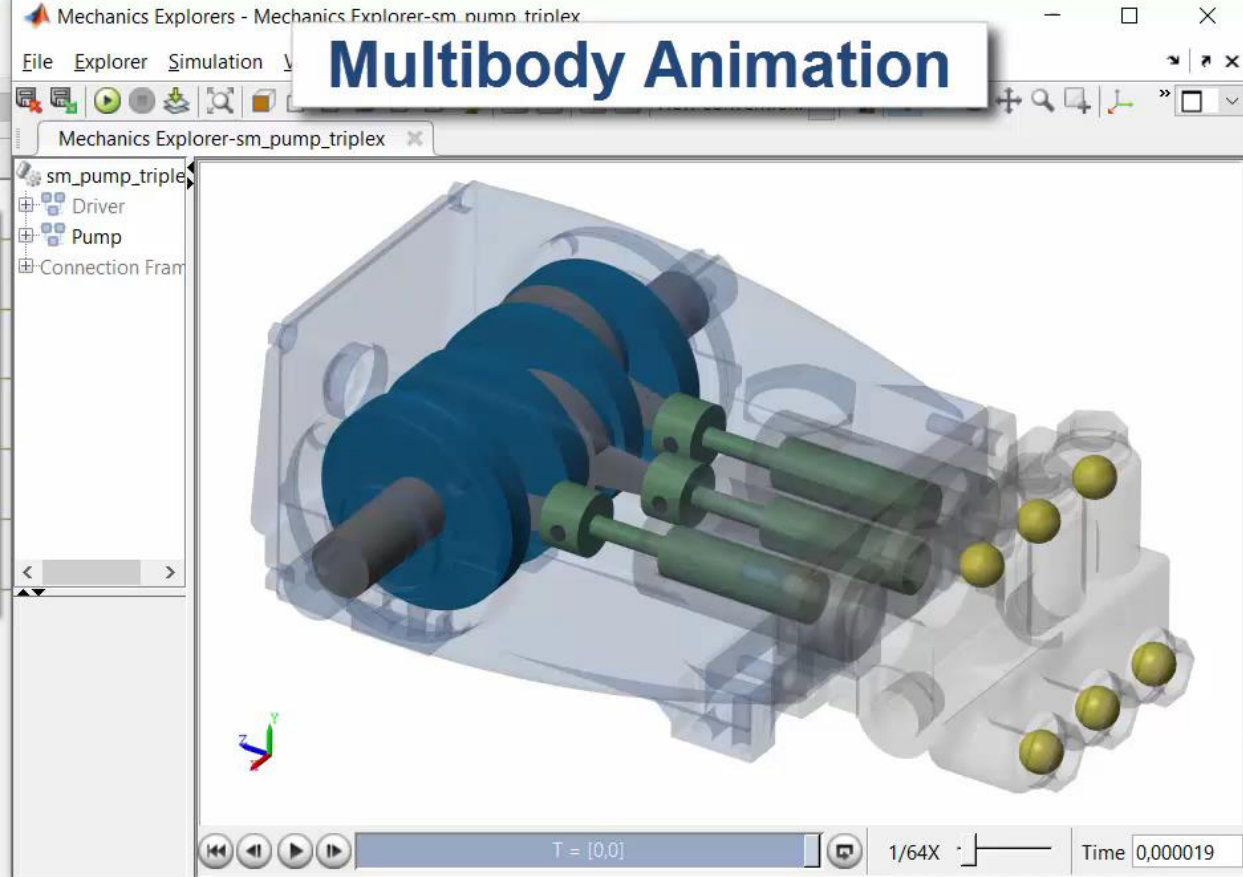


Triplex Pump with Faults

Simulation Results and Measured Data



Multibody Animation



pMeas

pMeas

Diagnostics: Off



No Fault



Blocked Inlet



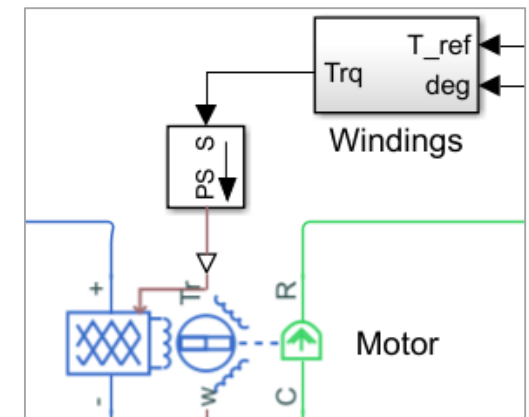
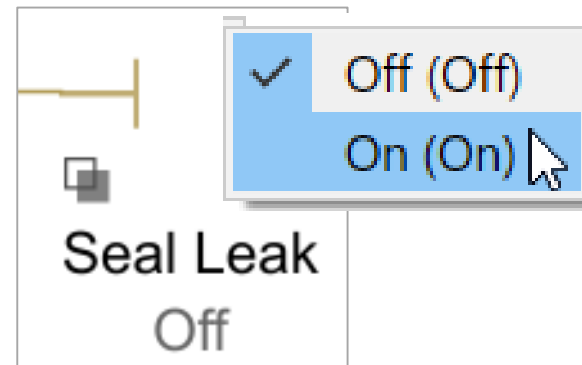
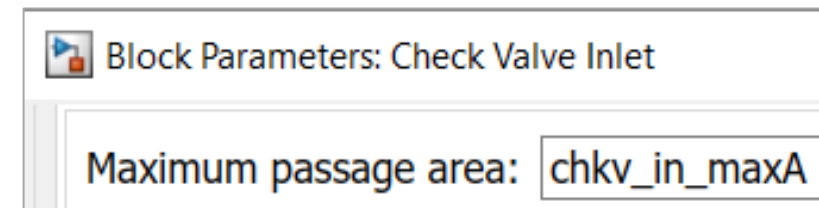
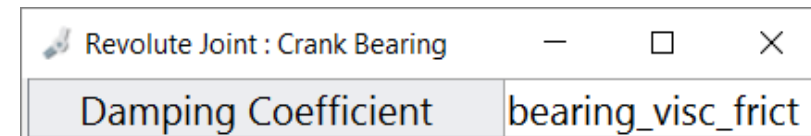
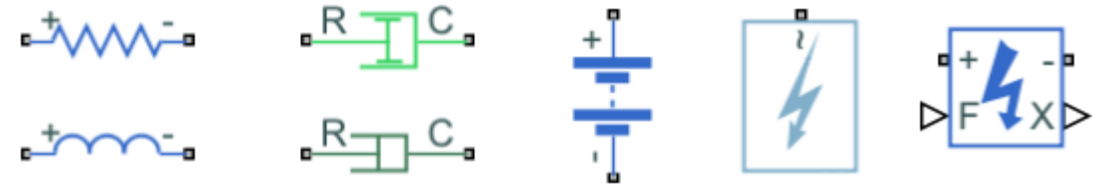
Seal Leak



Worn Bearing

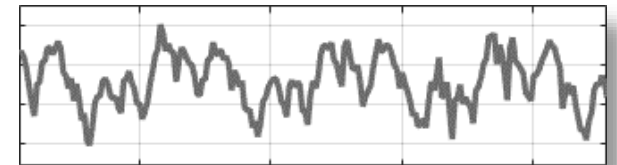
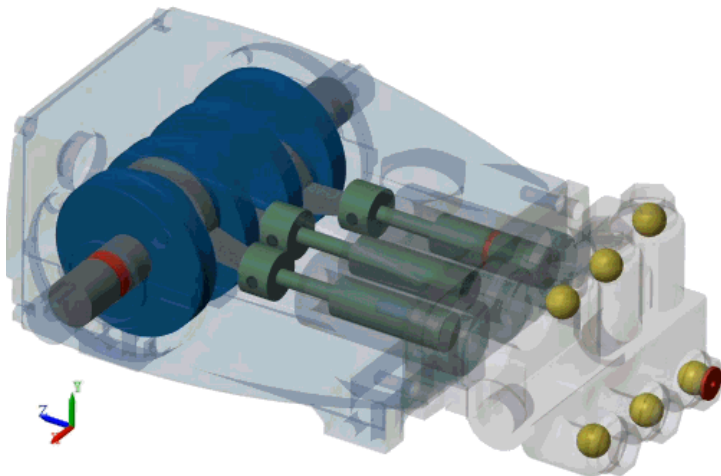
Model Component Failure

- Generic faults in many components
 - Short circuit, open circuit, friction, fade, etc.
 - Trigger based on time or conditions
- Adjust parameter values
 - Worn bearing adds friction
 - Blocked inlet has reduced passage area
- Adjust network
 - Seal leakage adds flow path
- Custom effects in Simulink
 - Broken winding applies no torque for 1/3 of every revolution



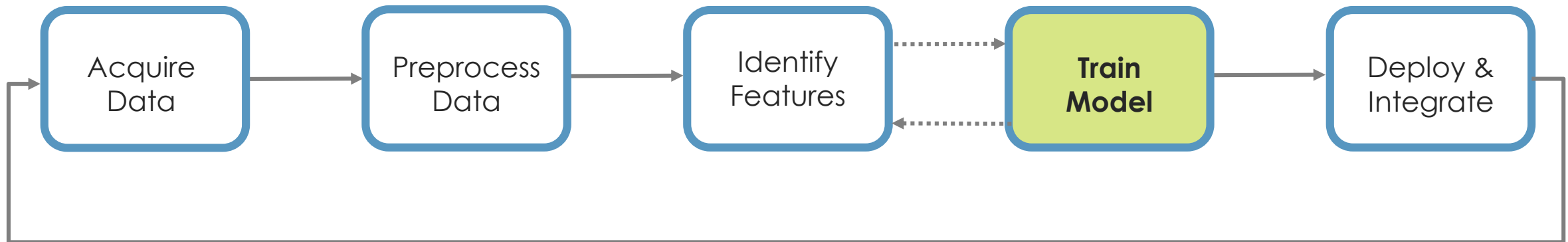
Demo: Generating failure data with a digital twin

- Scenario: We've already built and tuned our digital twin
- Goal: Generate synthetic failure data by running multiple simulations with varying levels of degradation/failure



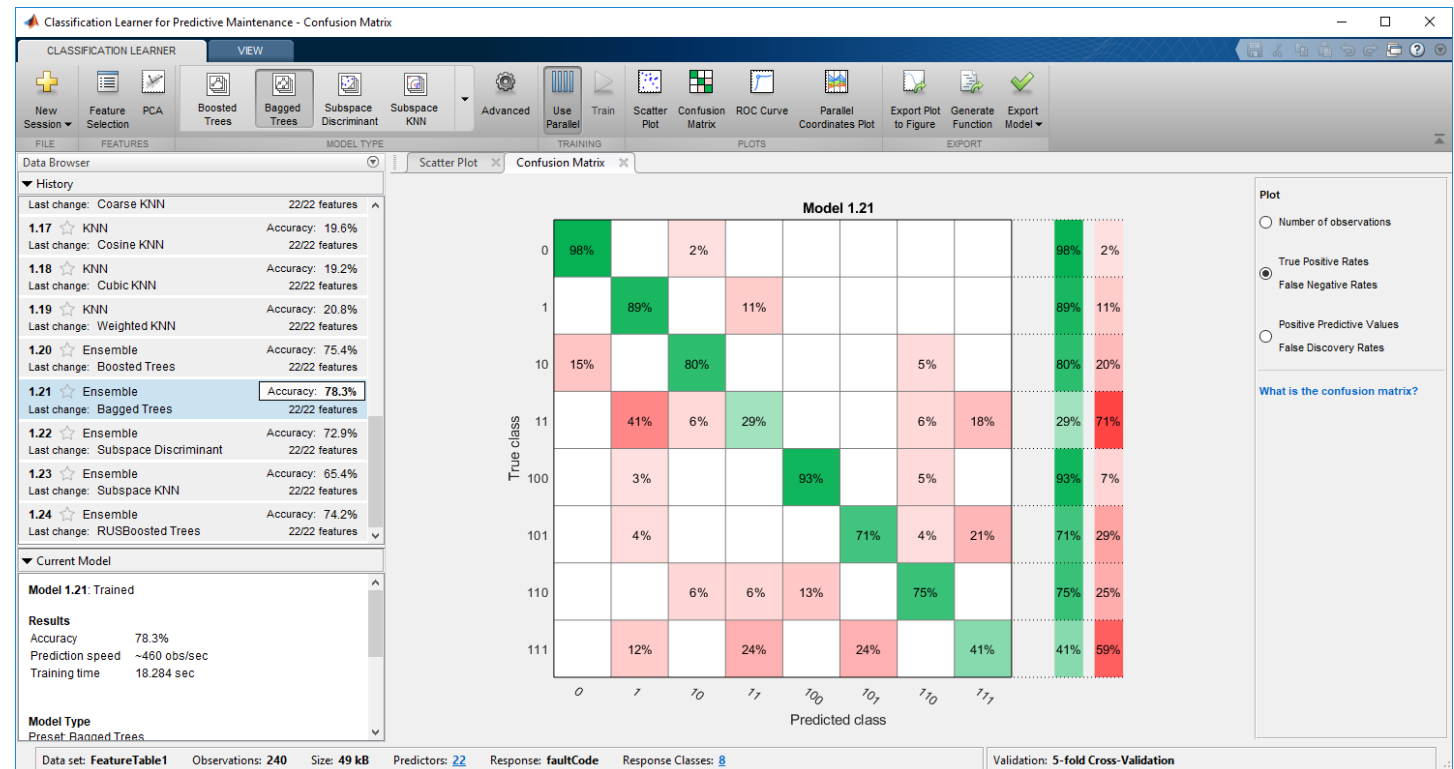
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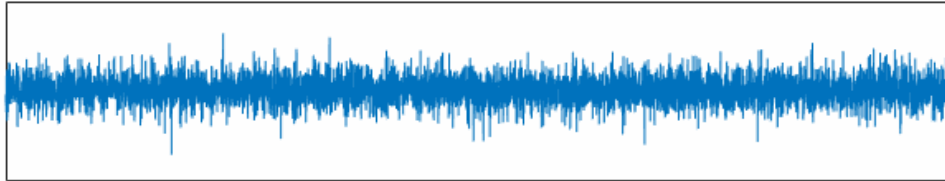


Demo: Create a Machine Learning Model for Condition Monitoring

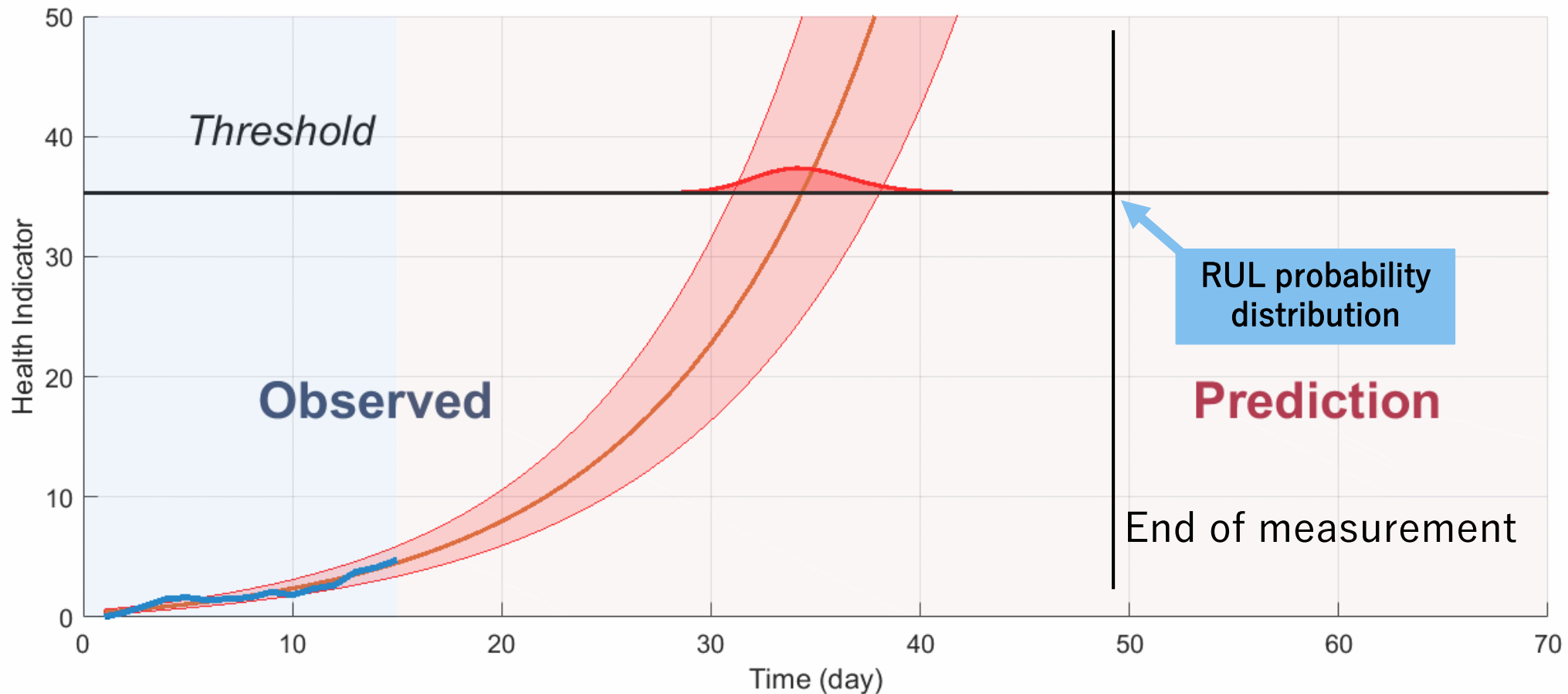
- Scenario: We have simulated data from all the failures (blockage, leakage, friction) and all of the possible combinations of these failures
- Goal: Create a classifier to identify the fault



Estimate Remaining Useful (RUL) to Determine When You Should Perform Maintenance

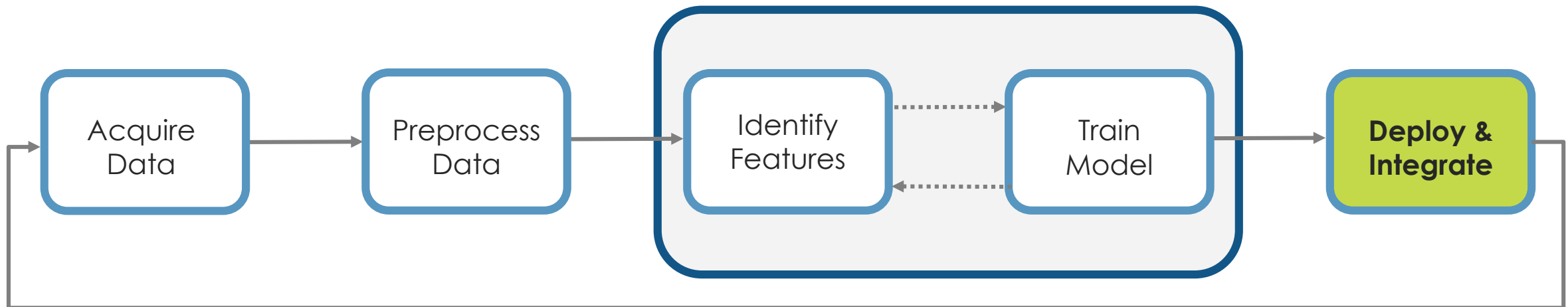


RUL: 459 hours
(95%CI: 374-558 hours)



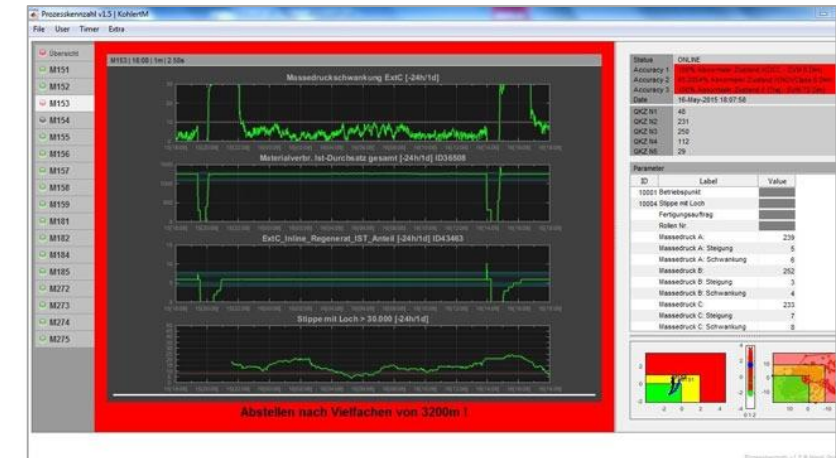
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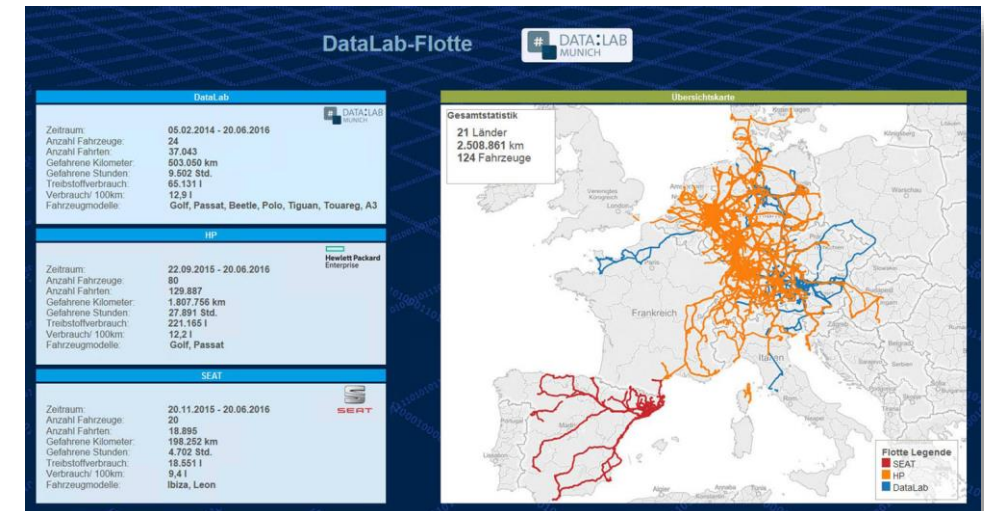


Challenges: Delivering results to your end users

- Maintenance needs simple, quick information
 - Hand held devices, Alarms
- Operations needs a birds-eye view
 - Integration with IT & OT systems
- Customers expect easy to digest information
 - Automated reports

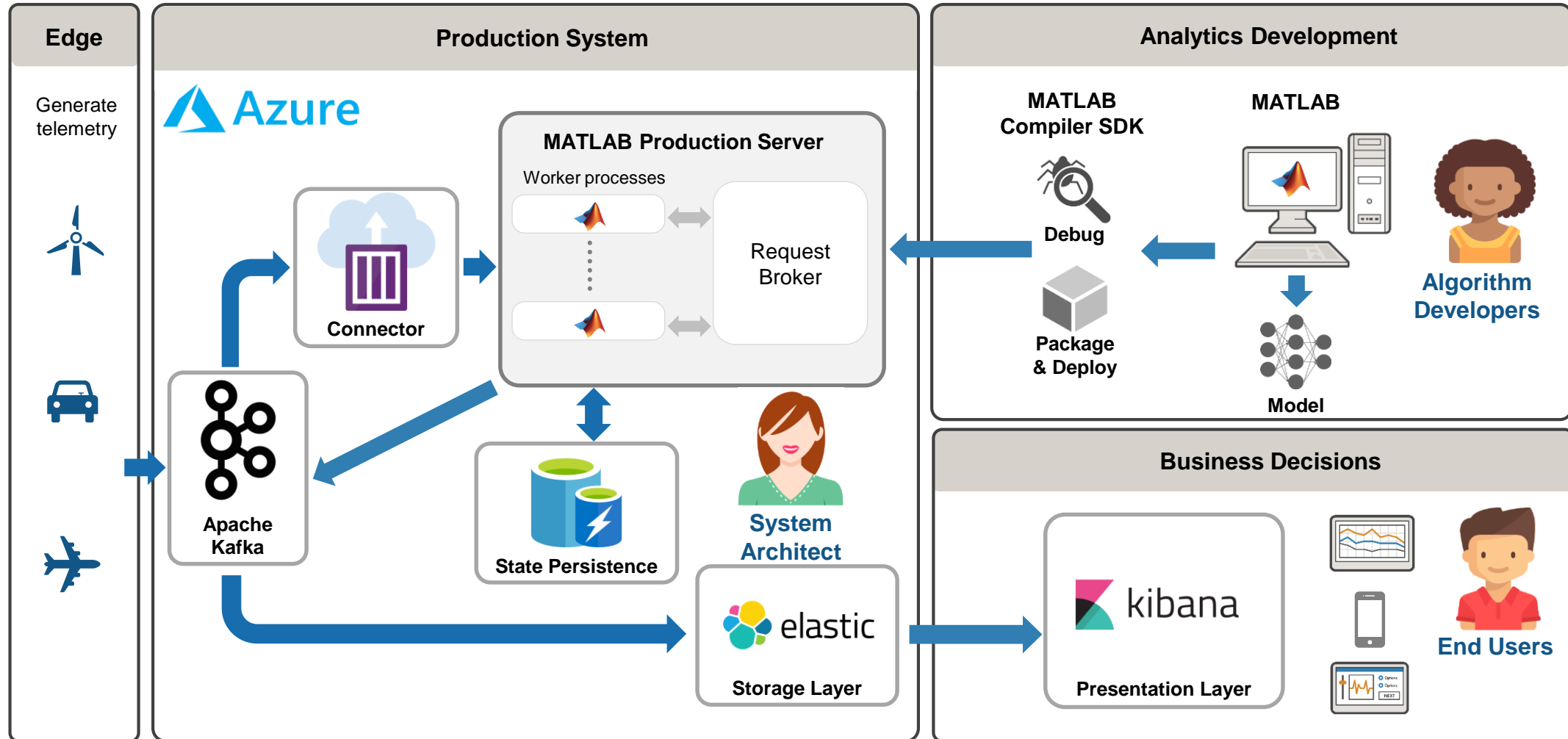


Dashboards

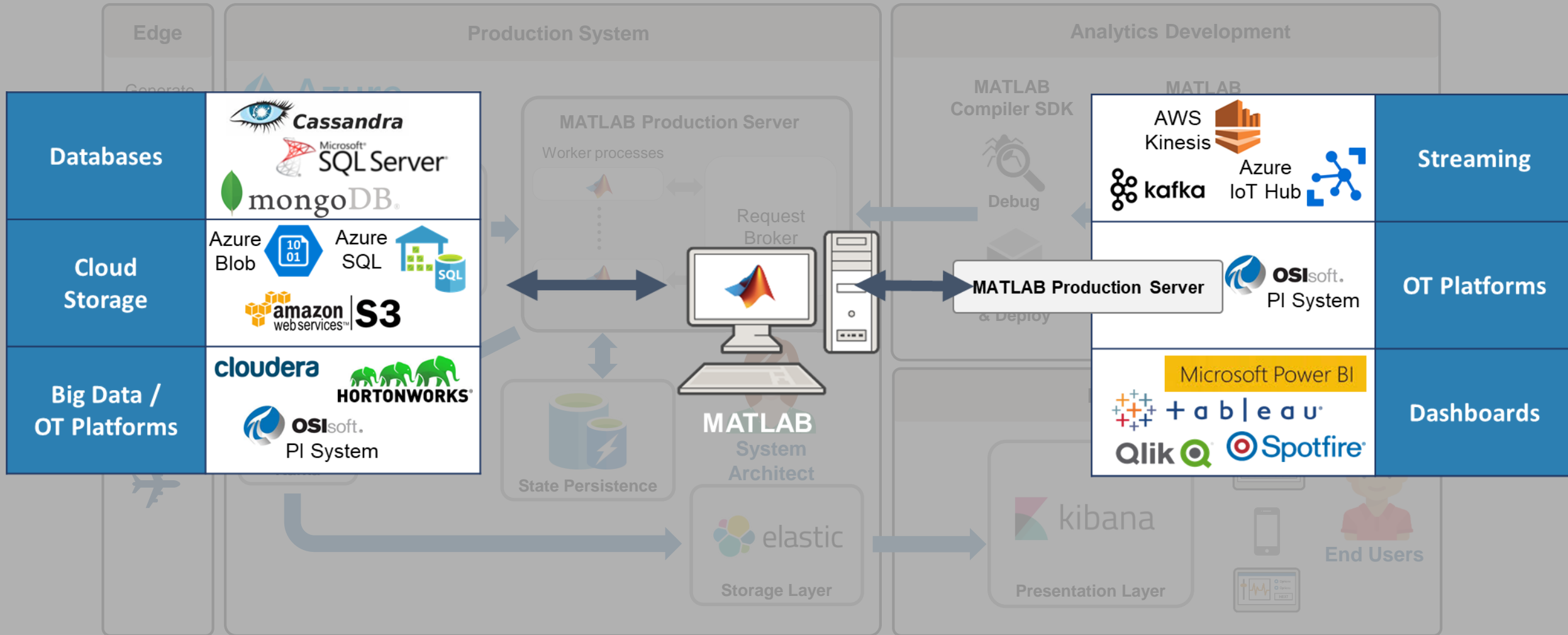


Fleet & Inventory Analysis

Predictive Maintenance Architecture on Azure

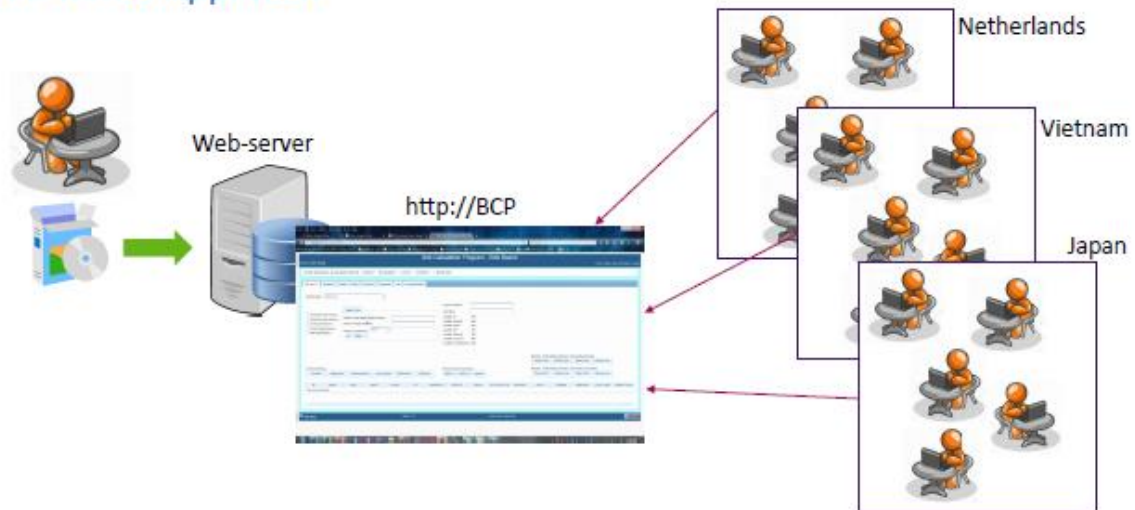


Predictive Maintenance Architecture on Azure



Bosch and SNCF Have Implemented Production Systems Running Today

Web-based Approach



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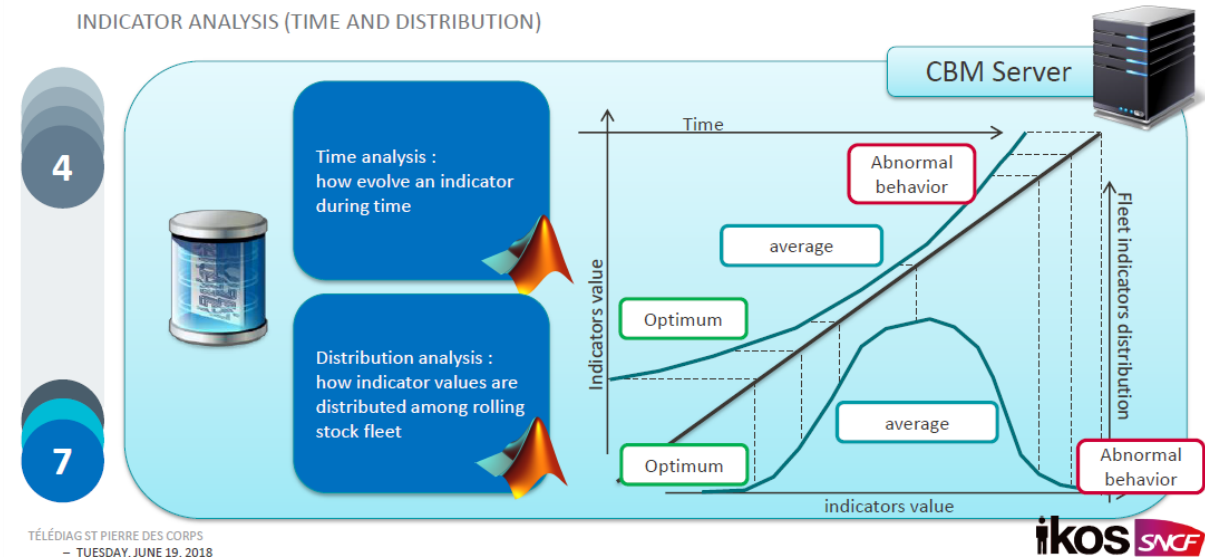
[Link to user story](#)

“Updating software is required only at 1 location...Maximum of 1 hour downtime for major updates...”

MATLAB EXPO 2019

CBM – PROGNOSTIC

INDICATOR ANALYSIS (TIME AND DISTRIBUTION)



[Link to user story](#)

“...[Our solution] optimizes the whole maintenance process without breaking the existing process...”

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MathWorks can help you get started TODAY

- [Examples](#)
- [Documentation](#)
- Tutorials & Workshops
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- [Tech Talk Series](#)

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CONTENTS

Predictive Maintenance Toolbox

Design and test condition monitoring and predictive maintenance algorithms

Predictive Maintenance Toolbox™ lets you label data and estimate the remaining useful life (RUL) of a machine.

The toolbox provides functions and an interactive app for ranking features using data-based and model-based methods, such as spectral, and time-series analysis. You can monitor time-series data using frequency and time-frequency methods. To estimate RUL, you can use survival, similarity, and trend-based models.

You can analyze and label sensor data imported from distributed file systems. You can also label simulated Simulink® models. The toolbox includes reference examples for batteries, and other machines that can be reused for maintenance and condition monitoring algorithms.

Getting Started

Learn the basics of Predictive Maintenance Toolbox

Manage System Data

Import measured data, generate simulated data, organize data

Preprocess Data

Clean and transform data to prepare it for extracting features

Identify Condition Indicators

Explore data at the command line or in the app to identify condition indicators

Detect and Predict Faults

Train decision models for condition monitoring and fault detection

Deploy Predictive Maintenance Algorithms

Implement and deploy condition-monitoring and predictive maintenance algorithms

Documentation
All
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CONTENTS

Detect and Diagnose Faults

or pump mechanics

ω → pump

Δ

inverse model

pump model

r1

relief hole

split seal with clearance gap

sliding ring seal

ball bearings

shaft

suction

Plunger 1

Plunger 2

Plunger 3

Housing

Revolute Crank

Crack

Out1

Out2

Out3

P1

P2

P3

Crack

Fault Diagnosis of Centrifugal Pumps Using Steady State Experiments

Use a model-based approach for detection and diagnosis of different types of faults in a pumping system.

Open Live Script

Fault Diagnosis of Centrifugal Pumps Using Residual Analysis

Use a model parity-equations-based approach for detection and diagnosis of faults in a pumping system.

Open Live Script

Multi-Class Fault Detection Using Simulated Data

Use a Simulink model to generate faulty and healthy data, and use the data to develop a multi-class classifier to detect different

Open Live Script

Analyze and Select Features for Pump Diagnostics

Use the Diagnostic Feature Designer app to analyze and select features to diagnose faults in a triplex reciprocating pump.

Open Live Script

Friction Change Detection

Use an extended Kalman filter for online estimation of the friction of a simple DC motor. Significant changes in the estimated friction are

Open Script

Power Spectrum

Use a data-based modeling approach for fault detection.

Open Script

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