Condition Monitoring Using Statistical & Machine Learning Models in PI AF

Ionut Buse

TC Energy

TC Energy

One of North America's Largest Natural Gas Pipeline Networks

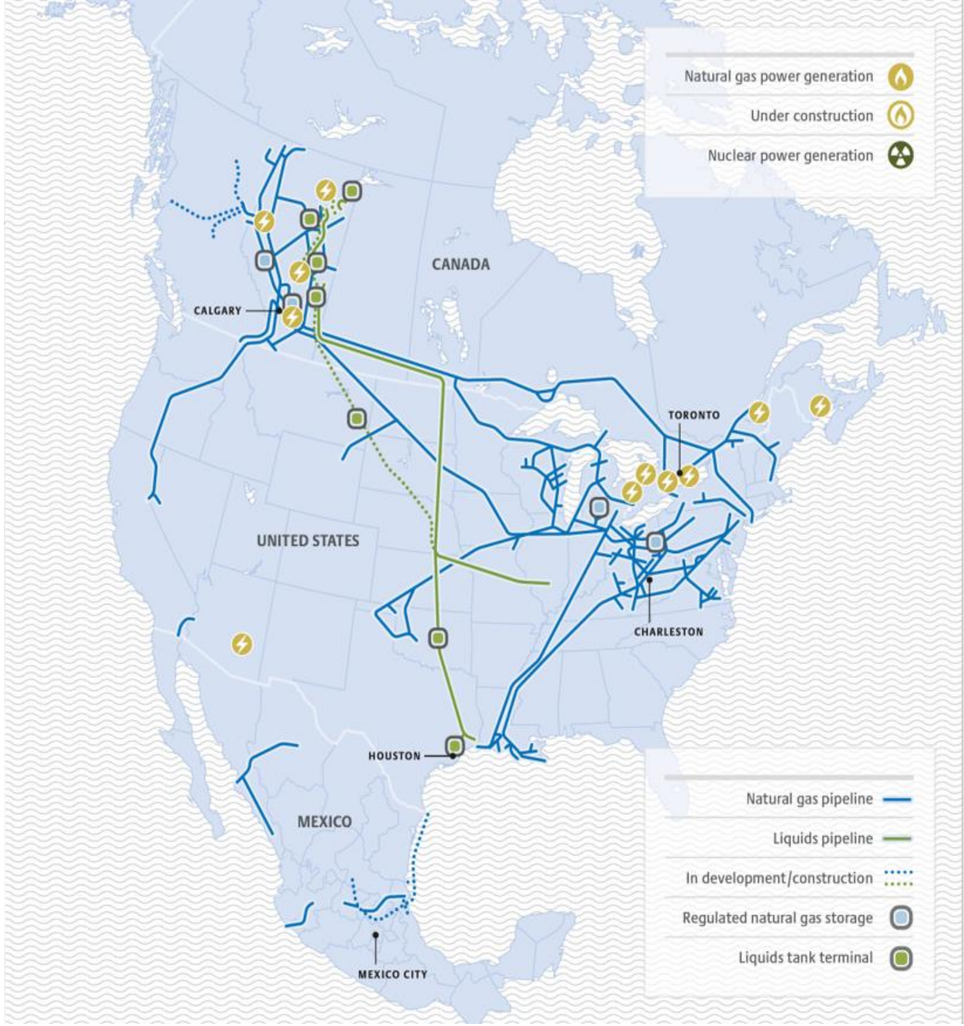
- Operate 91,900 km (57,100 mi.) of pipelines
- Transport ~25 per cent of continental demand
- Over 650 BCF of gas storage capacity

One of Canada's Largest Private Sector Power Generators

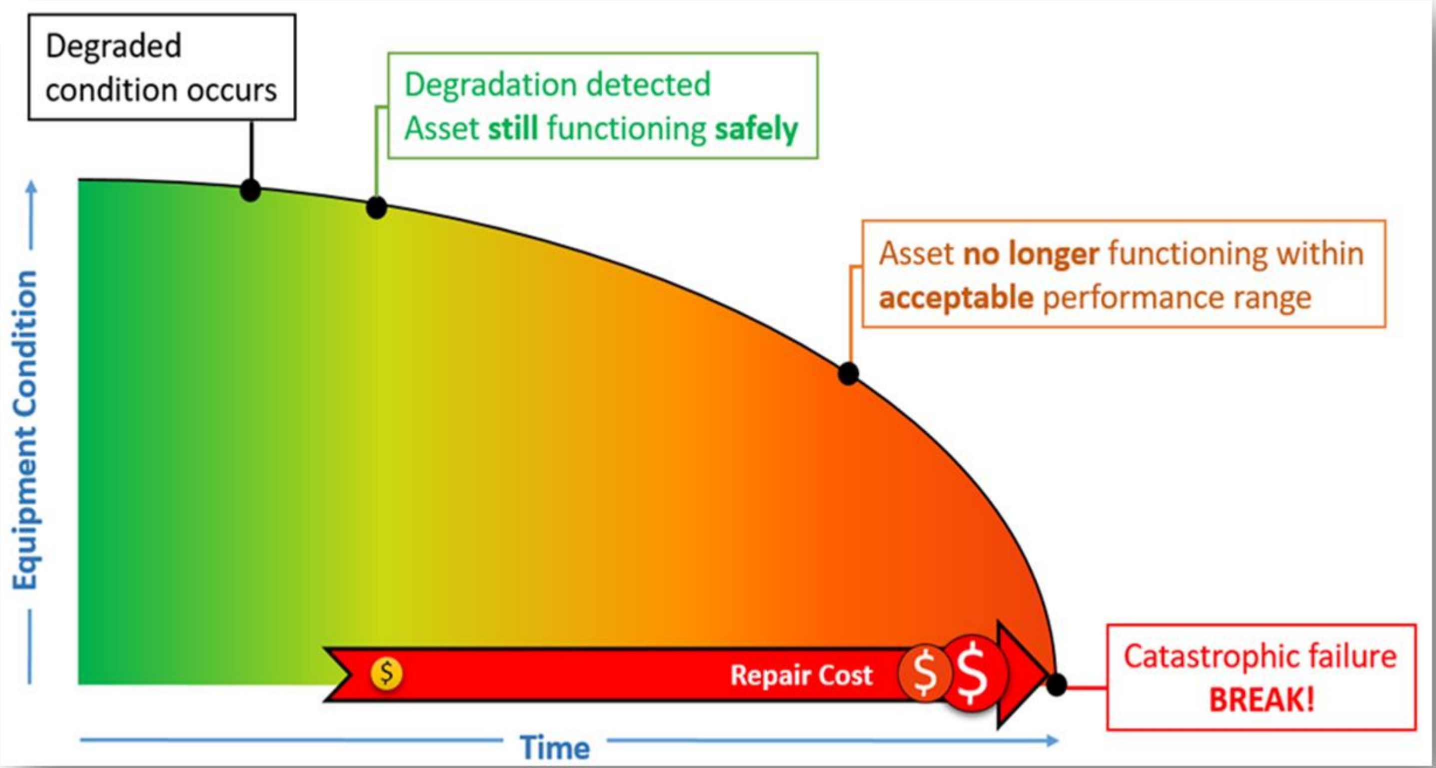
- 11 power facilities, approximately 6,600 MW
- Low-emissions portfolio includes nuclear and natural gas generation

Premier Liquids Pipeline System

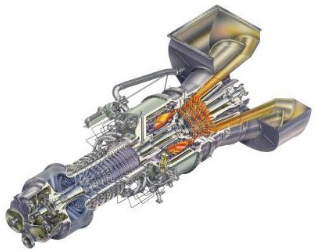
- 4,900 km (3,000 mi.) of pipelines
- Keystone System transports ~20 per cent of Western Canadian exports
- Safely delivered more than 2 billion barrels of Canadian oil to U.S. markets

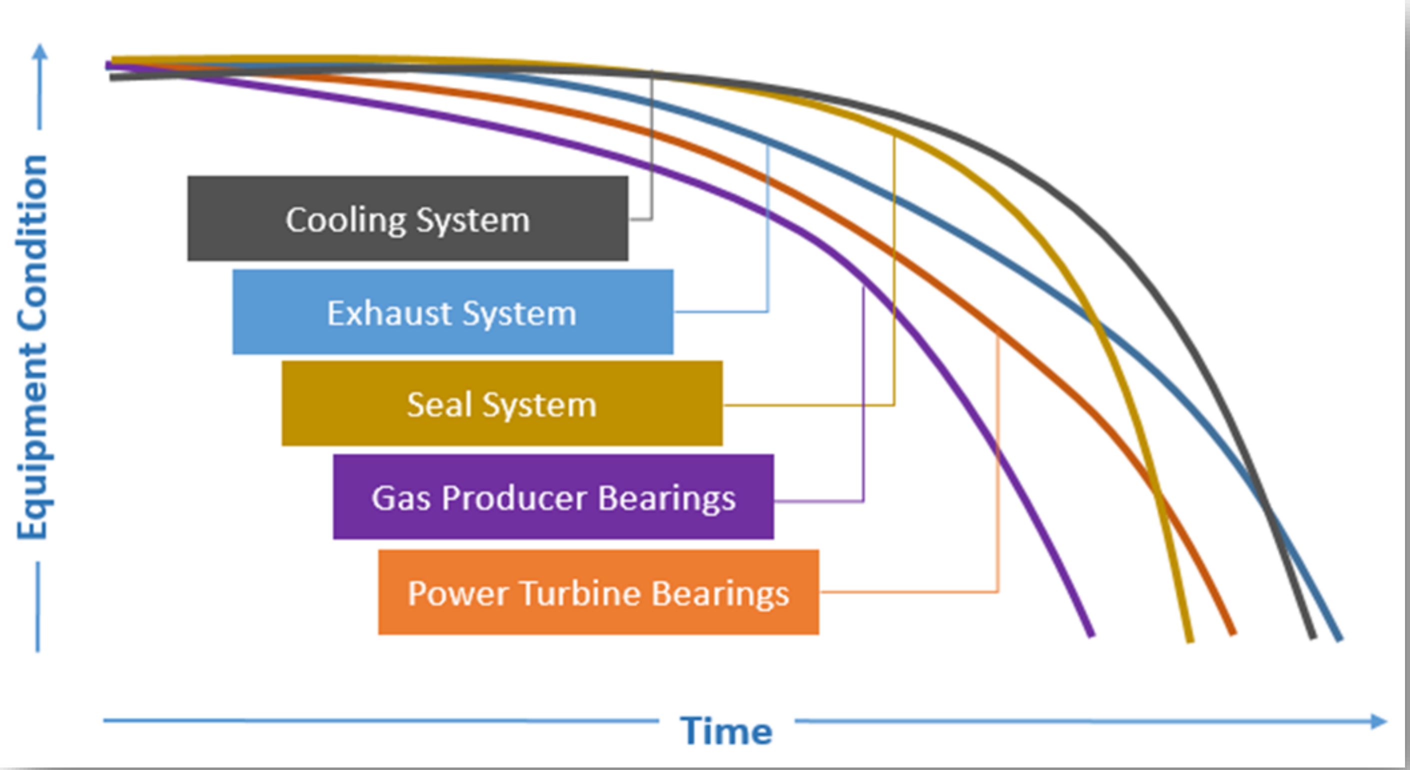


Realtime Condition Monitoring

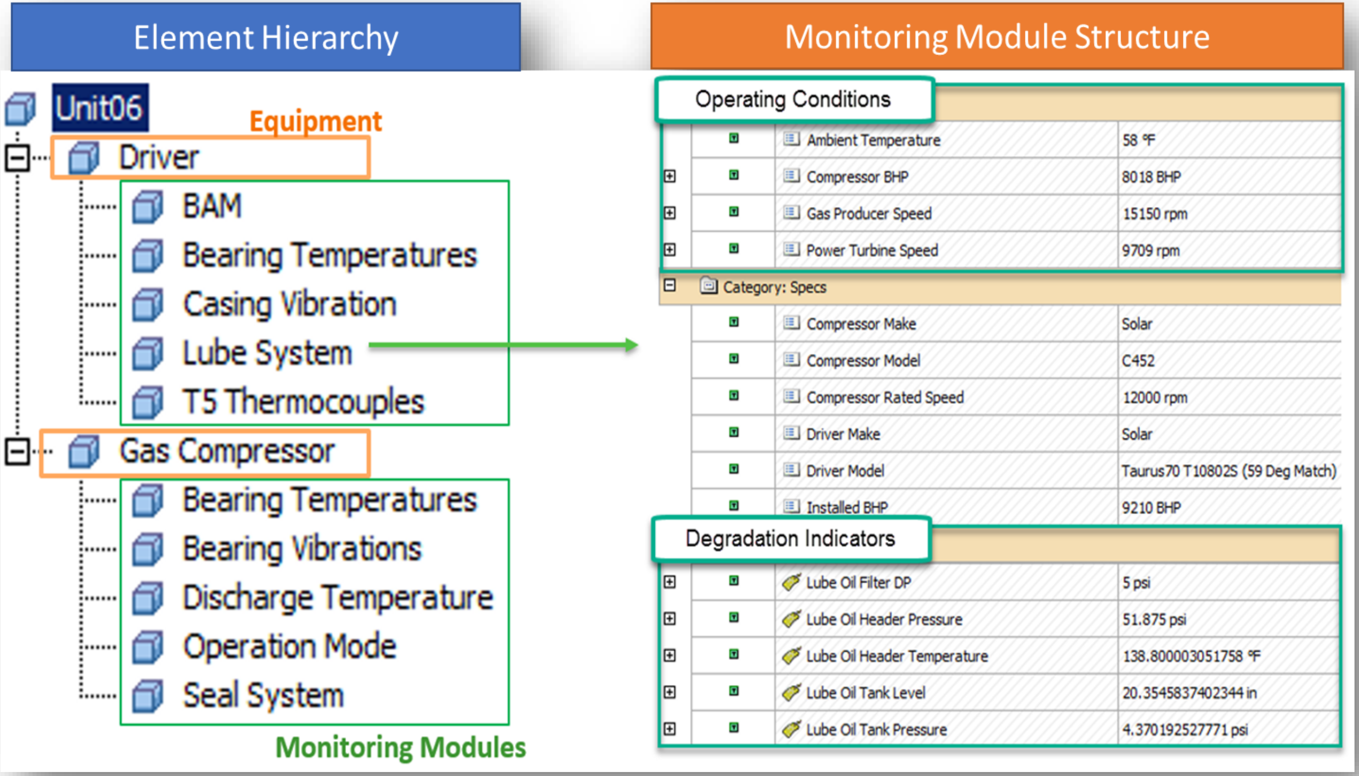


Realtime Condition Monitoring | In Practice



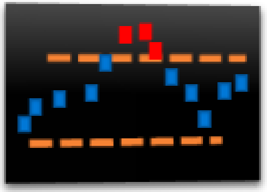


Asset Digital Transformation



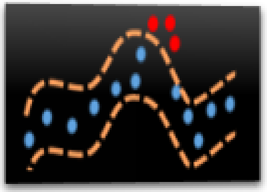
Anomaly Detection Methodology

Statistical & Machine Learning Algorithms



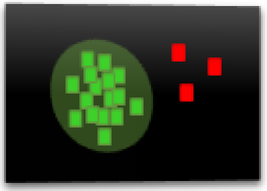
Statistical Quality Control (SQC)

Highly scalable anomaly detection technique that uses descriptive statistics to compute static thresholds. Given the historical mean (μ) and standard deviation (σ) for a sensor, anomalies can be flagged when new readings fall outside [μ-3σ,μ+3σ]



Regression

Regression models can be used to predict a sensor reading (predicted variable), given one or more variables (predictors). Dynamic thresholds can be set up around the prediction, providing a more accurate anomaly detection approach



Clustering

Clustering models can discover and learn subtle relations between many variables and group similar data into clusters. New sensor data that is significantly different from the existing clusters can be flagged as abnormal

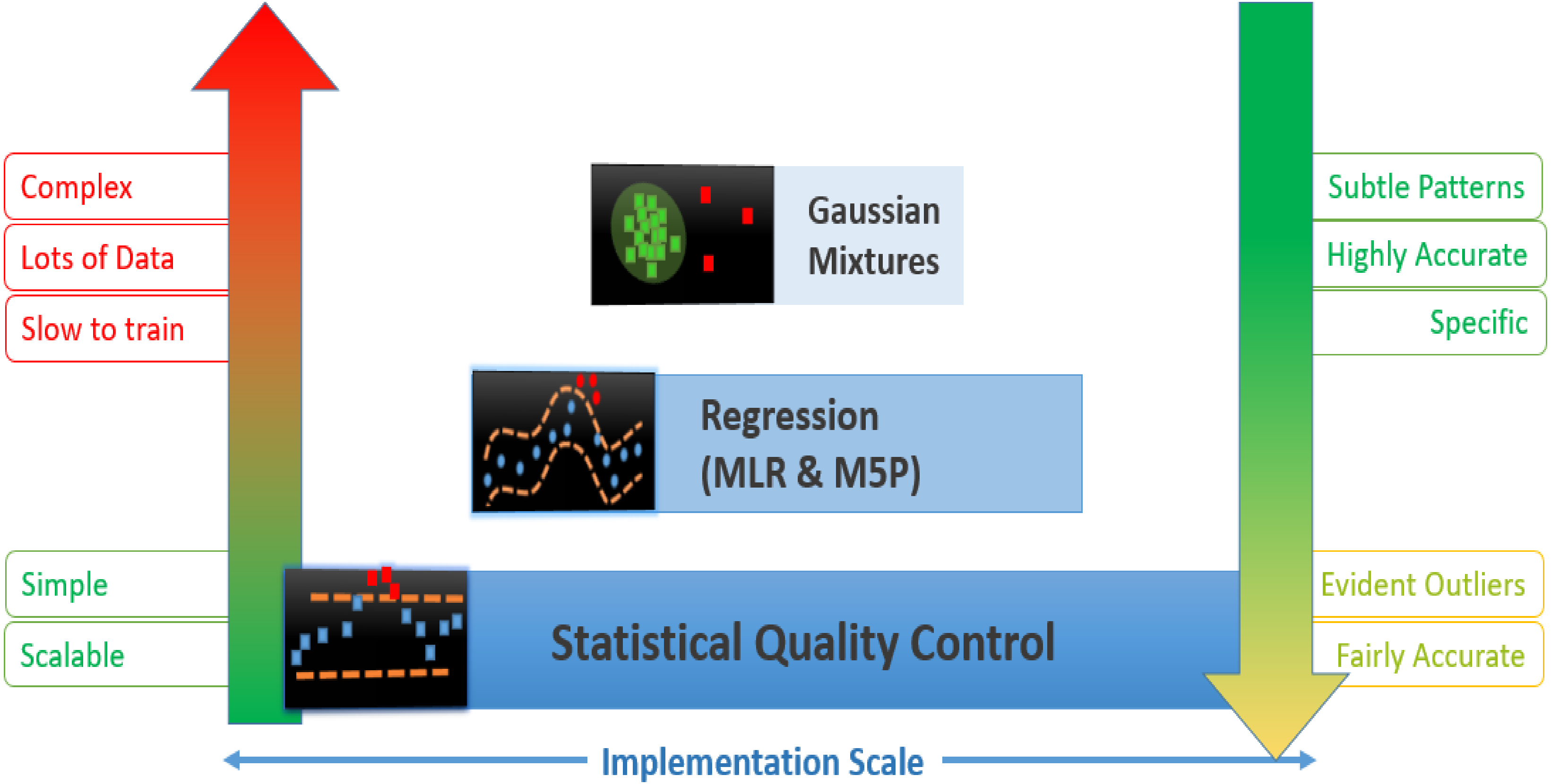
Anomaly Detection Methodology

Statistical & Machine Learning Algorithms

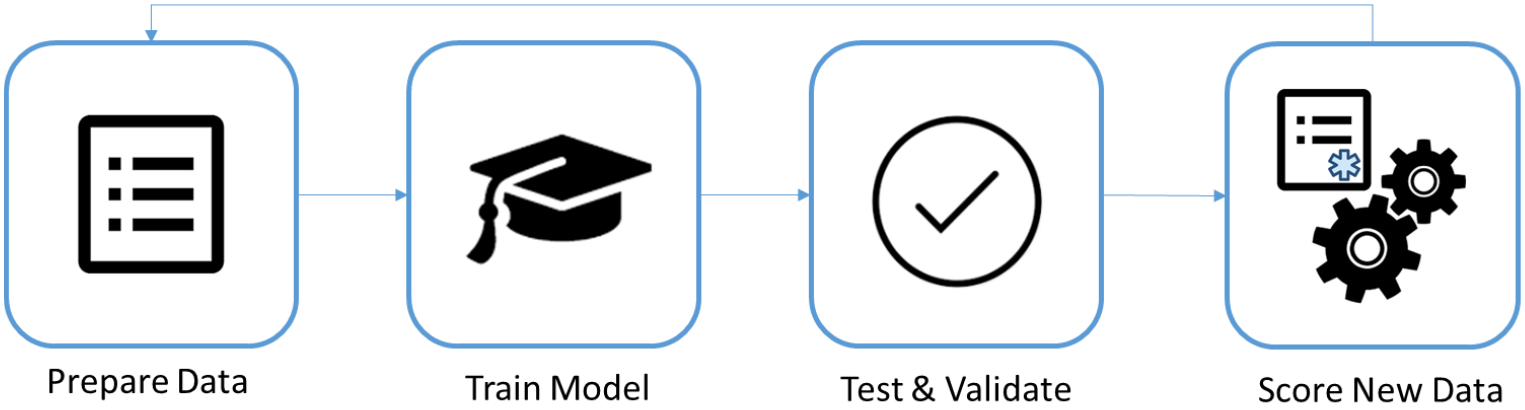
	Class	Multivariable	Training Speed	Dataset Size	Complexity	Accuracy
SQC	Process Control	No	Fast	Small	Simple	OK in most cases
MLR	Regression	Yes	Fast	Medium	Fairly Simple	Accurate w/ linear relations
M5P	Regression	Yes	Medium	Medium	Complex	Accurate w/ linear & non-linear relations
Gaussian Mixture	Clustering	Yes	Slow	Large	Very Complex	Highly accurate

Anomaly Detection Methodology

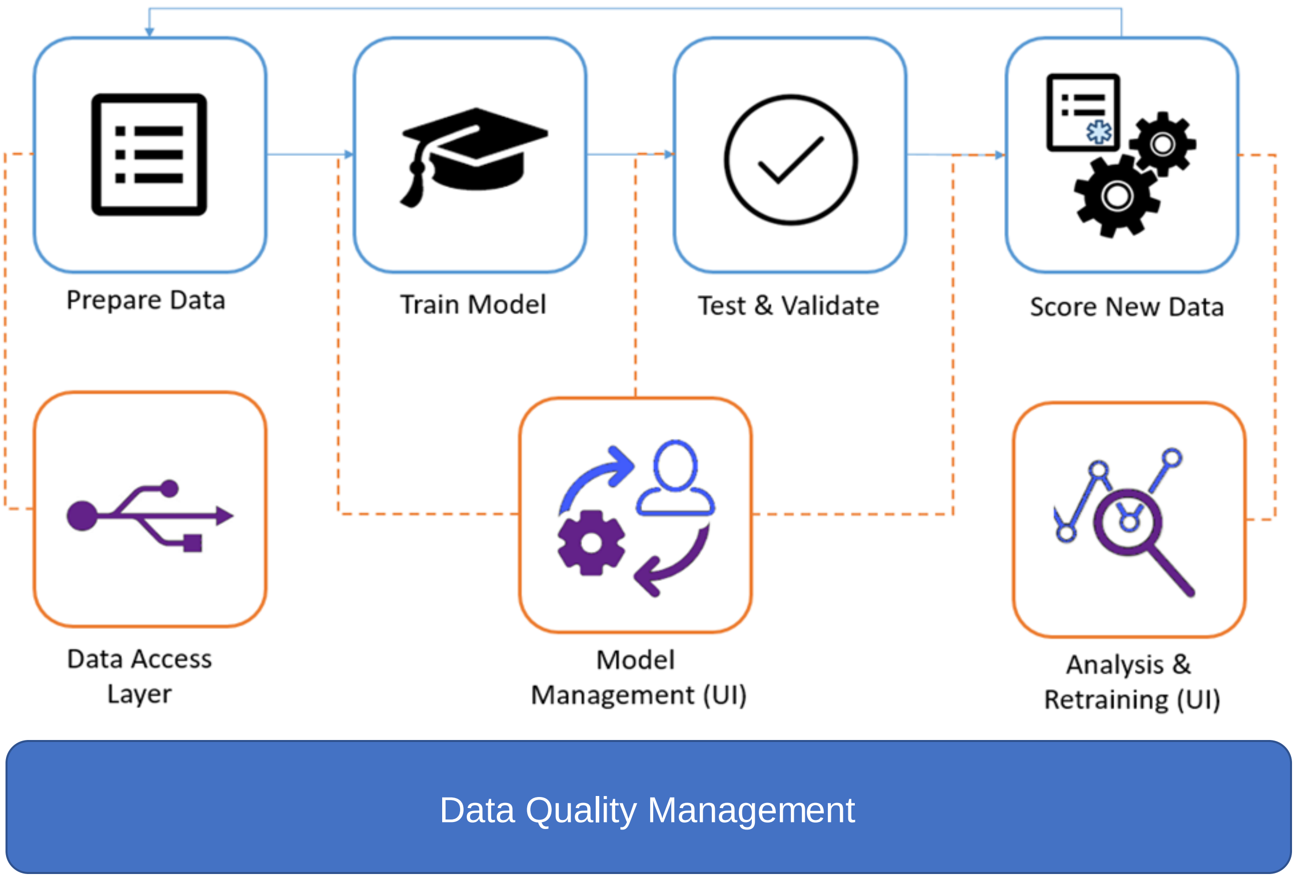
Stacked Complexity Approach



Traditional Anomaly Detection Methodology



Our Approach to Anomaly Detection



Technology Layers | PI AF is Foundational

Custom Front-End
AngularJS

REST Web Services
.NET Technologies | AFSDK | Accord.Net

PI Vision
OpsVision

SQL Server

PI Asset Framework
Element Templates | PI Analysis | PI Event Frames | PI Notifications

Digital Twins

Engr Equations

Eval Models

Notify Anomalies

Anomaly Detection Implementation

Statistical Quality Control (SQC) | Model Training

Anomaly Detection Implementation

Statistical Quality Control (SQC) | PI AF Attribute Construct

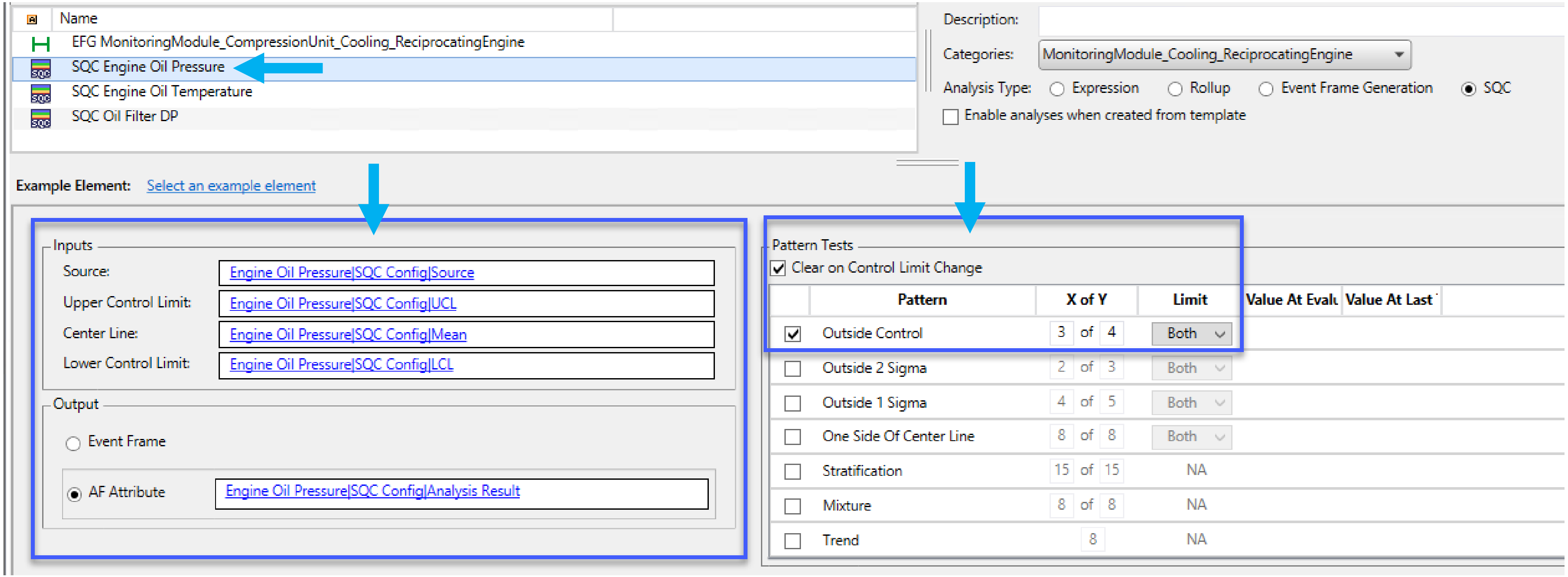
Driver | Cooling Monitoring Module

Name	Description	Value
Category: Degradation Indicators		
Engine Oil Inlet Temperature		0 °F
Engine Oil Pressure		0 psi
_triggerId	Unique identifier for the trigger input	11
Panel Config		
Precision	Significant digits for presentation purpose	3
Rounded Value		0
SQC Config		
_modelId	-1 if model is not trained	0
Analysis Result	Result of the SQC Pattern Test	
LCL	Lower Control Limit	0
Mean	Historical average at steady state	0
Model Info		
Source	Applies defaults and statistical precision to the raw input	0
State	Instantaneous state	
Statistical Precision	Significant digits for Anomaly Detection	1
StdDev	Historical standard deviation at steady state	0
Threshold Adjustment Factor	StdDev multiplier to adjust thresholds	0
UCL	Upper Control Limit	0
Oil Filter DP		0 psi

Anomaly Detection Implementation

Statistical Quality Control (SQC) | PI AF Analysis – Standard Functionality

Driver | Cooling Monitoring Module



Anomaly Detection Implementation

Multivariate Linear Regression (MLR) | Model Training

Anomaly Detection Implementation

Multivariate Linear Regression (MLR) | PI AF Attribute Construct

Driver | Cooling Monitoring Module

Attribute	Description	Value
Engine Oil Pressure		0 psi
_triggerId	Unique identifier for the trigger input	11
Panel Config		
Precision	Significant digits for presentation purpose	3
Regression Config	Special construct that enables Regression Anomaly Detection	
_enforced	If enforced it will trigger anomalies if model is not trained	False
_linear		True
_modelId	-1 if model is not trained	0
Model Coefficients	Lookup coefficients for linear regression models. Names need to match attributes in this module template.	
_intercept		0
Ambient Temperature		0
Engine Oil Inlet Temperature		0
Engine Speed		0
Model Info		
Prediction		0
Predictors	Attribute names to be used as predictors. Must be exact match to attributes in this module template	String Array
RMSE	Root Mean Squared Error on training dataset	0
Source	Applies defaults and statistical precision to the raw input	0
State	Instantaneous state	
Statistical Precision	Significant digits for anomaly detection	1
Threshold Adjustment Factor	RMSE multiplier to adjust thresholds	0

Anomaly Detection Implementation

Multivariate Linear Regression (MLR) | PI AF Analysis

Driver | Cooling Monitoring Module

MLR Engine Oil Pressure Analysis

EFG MonitoringModule_CompressionUnit_Cooling_ReciprocatingEngine
MLR Engine Oil Pressure
SQC Engine Oil Pressure
SQC Engine Oil Temperature
SQC Oil Filter DP

Categories: MonitoringModule_Cooling_ReciprocatingEngine
Analysis Type: Expression / Rollup / Event Frame Generation / SQC
Enable analyses when created from template

Example Element: Select an example element

Add a new variable

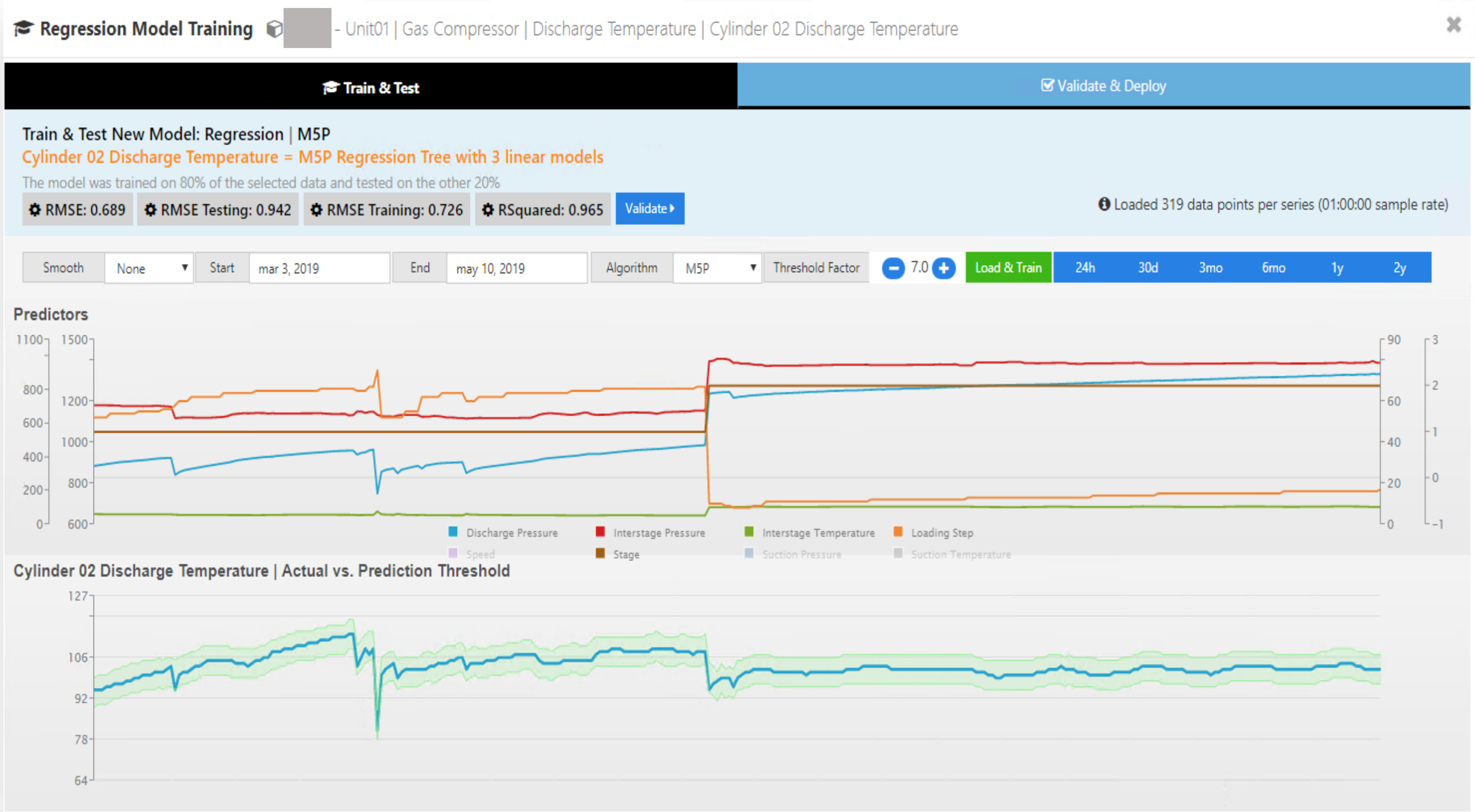
Leverage Attribute Construct to evaluate linear regression model

Write Prediction back to Attribute Construct

<table>
<tr><th>Name</th><th>Expression</th><th>Output Attribute</th></tr>
<tr><td>vSteadyState</td><td>'Steady State'</td><td>Map</td></tr>
<tr><td>predictedVariable</td><td>'Engine Oil Pressure'</td><td>Map</td></tr>
<tr><td>precision</td><td>'Engine Oil Pressure|Regression Config|Statistical Precision'</td><td>Map</td></tr>
<tr><td>modelIsTrained</td><td>//if model id = -1 then model does not exists in the SQL database
'Engine Oil Pressure|Regression Config|_modelId' <> -1</td><td>Map</td></tr>
<tr><td>enforced</td><td>'Engine Oil Pressure|Regression Config|_enforced'</td><td>Map</td></tr>
<tr><td>rmse</td><td>'Engine Oil Pressure|Regression Config|RMSE'</td><td>Map</td></tr>
<tr><td>rmseMultiplier</td><td>'Engine Oil Pressure|Regression Config|Threshold Adjustment Factor'</td><td>Map</td></tr>
<tr><td>intercept</td><td>//model coefficients
'Engine Oil Pressure|Regression Config|Model Coefficients|_intercept'</td><td>Map</td></tr>
<tr><td>c1</td><td>'Engine Oil Pressure|Regression Config|Model Coefficients|Ambient Temperature'</td><td>Map</td></tr>
<tr><td>c2</td><td>'Engine Oil Pressure|Regression Config|Model Coefficients|Engine Speed'</td><td>Map</td></tr>
<tr><td>c3</td><td>'Engine Oil Pressure|Regression Config|Model Coefficients|Engine Oil Inlet Temperature'</td><td>Map</td></tr>
<tr><td>v1</td><td>//input variables
if BadVal('Ambient Temperature') then 0 else 'Ambient Temperature'</td><td>Map</td></tr>
<tr><td>v2</td><td>if BadVal('Engine Speed') then 0 else 'Engine Speed'</td><td>Map</td></tr>
<tr><td>v3</td><td>if BadVal('Engine Oil Inlet Temperature') then 0 else 'Engine Oil Inlet Temperature'</td><td>Map</td></tr>
<tr><td>prediction</td><td>if vSteadyState and modelIsTrained
then intercept + c1 * v1 + c2 * v2 + c3 * v3 else 0</td><td>Engine Oil Pressure|Regression Config|Prediction|Model Output</td></tr>
<tr><td>predictionLowerThreshold</td><td>if vSteadyState and modelIsTrained
then Roundfrac(prediction - rmseMultiplier * rmse, precision) else 0</td><td>Engine Oil Pressure|Regression Config|Prediction|Threshold Lower</td></tr>
<tr><td>predictionUpperThreshold</td><td>if vSteadyState and modelIsTrained
then Roundfrac(prediction + rmseMultiplier * rmse, precision) else 0</td><td>Engine Oil Pressure|Regression Config|Prediction|Threshold Upper</td></tr>
<tr><td>source</td><td>//adjusts the raw data for the variable we are trying to predict
if BadVal(predictedVariable)
then '\Configuration|Regression Defaults|SOURCE'
else Roundfrac(predictedVariable, precision)</td><td>Engine Oil Pressure|Regression Config|Source</td></tr>
<tr><td>state</td><td>if predictedVariable = "Data Not Available" then 0 //Not Applicable
else if Not(vSteadyState) then 0 //Not Applicable
else if Not(modelIsTrained) and Not(enforced) then 0 //Not Applicable
else if Not(modelIsTrained) and enforced then 2 //Outside Tolerance
else if BadVal(source) or source > predictionUpperThreshold or source < predictionLowerThreshold then
else if source <= predictionUpperThreshold and source >= predictionLowerThreshold then 1 //Within Toler
else 0</td><td>Engine Oil Pressure|Regression Config|State</td></tr>
</table>

Anomaly Detection Implementation

Non-Linear Regression | Model Training

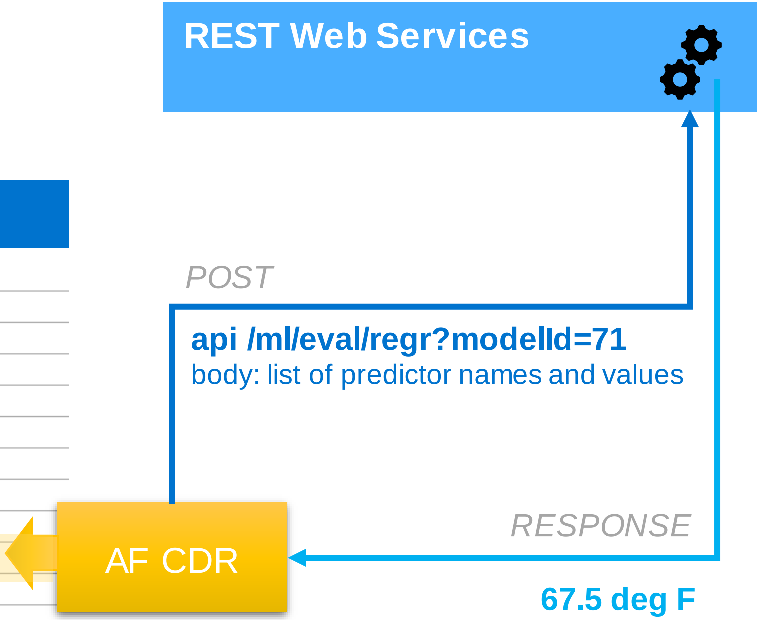


Anomaly Detection Implementation

Non-Linear Regression | AF Attribute Construct

Gas Compressor | Discharge Temperature Monitoring Module

Cylinder 02 Discharge Temperature		0 °
_triggerId	Unique identifier for the trigger input	14
Precision	Significant digits for presentation purpose	0
Regression Config	Special construct that enables Regression Anomaly Detection	
_enforced	If enforced it will trigger anomalies if model is not trained	False
_linear		False
_modelId	-1 if model is not trained	0
Model Info		
Prediction		0
Evaluation Request	Uses custom data reference to evaluate the model through REST call to ML Server	0
Model Output	If linear regression, evaluate natively in AF. If nonlinear, use custom data reference.	0
Threshold Lower		0
Threshold Upper		0
Predictors	Attribute names to be used as predictors. Must be exact match to attributes in this module template	String Array
RMSE	Root Mean Squared Error on training dataset	0
Source	Applies defaults and statistical precision to the raw input	0
State	Instantaneous state	NA
Statistical Precision	Significant digits for anomaly detection	1
Threshold Adjustment Factor	RMSE multiplier to adjust thresholds	0
Rounded Value		0



Anomaly Detection Implementation

Gaussian Mixture Model (GMM) | Model Training

Anomaly Detection Implementation

Gaussian Mixture Model (GMM) | Attribute Construct

REST Web Services

POST

api/ml/eval/clust?modelId=12
body: list of feature names and values

Driver | T5 Temperature Monitoring Module

Category: Pattern Recognition

Attribute	Value	Description
T5 Thermocouples Pattern		
_triggerId	15	Unique identifier for the trigger input
Clustering Config		
_modelId	-1	-1 if model is not trained
Features	String Array	Attribute names to be used as features. Must be exact match to attributes in this module template
Model Info		
Prediction		
Evaluation Request	0	Uses custom data reference to evaluate the model through REST call to ML Server
Overall LogLikelihood	0	
Predicted Cluster Index	0	
Predicted Cluster Label		
Predicted Cluster Type	0	0 = Normal, 1 = Abnormal
State	NA	Instantaneous state

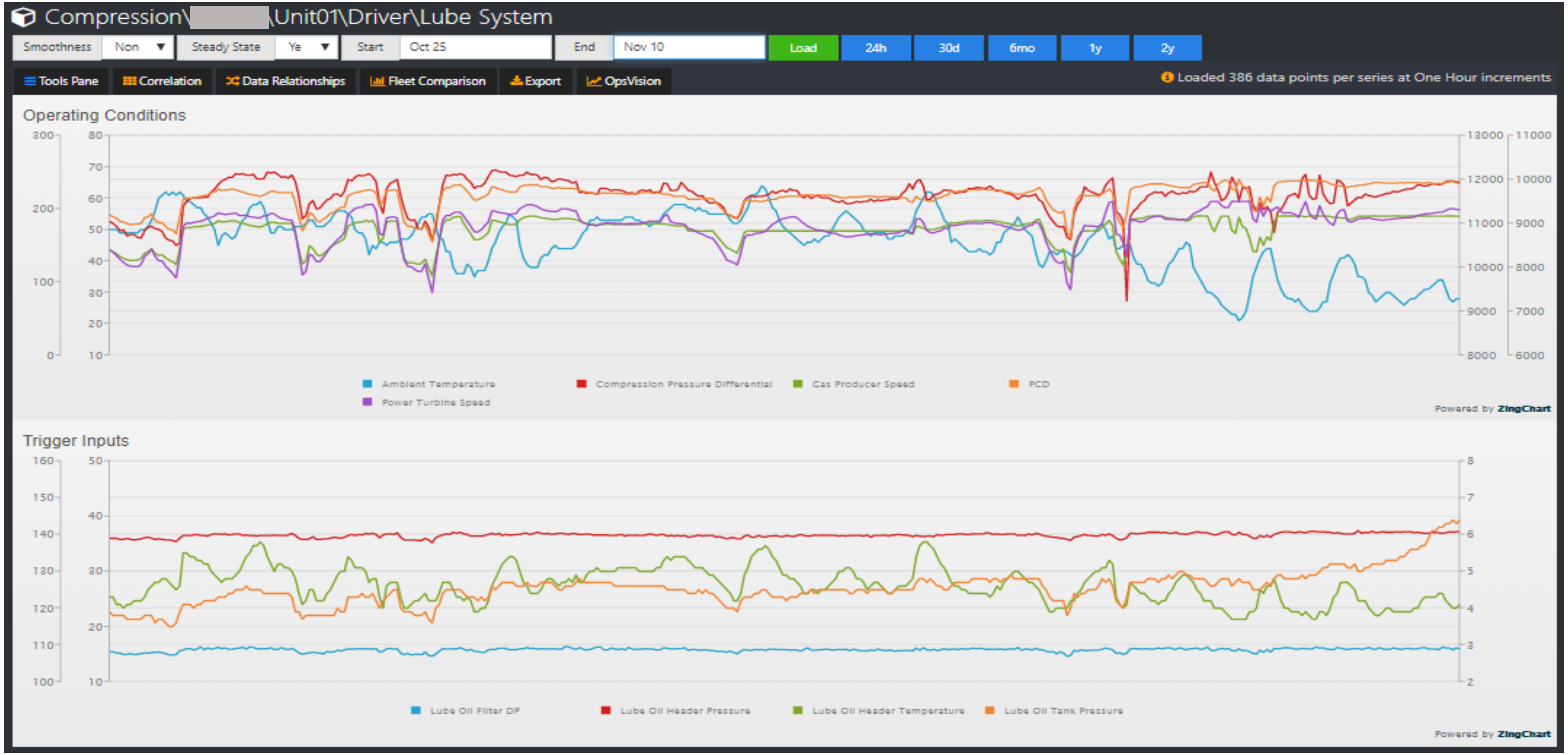
AF CDR

RESPONSE

```
{
  overall_LL: -286,
  clust_indx: 3,
  clust_label: clust03,
  clust_type: 0
}
```

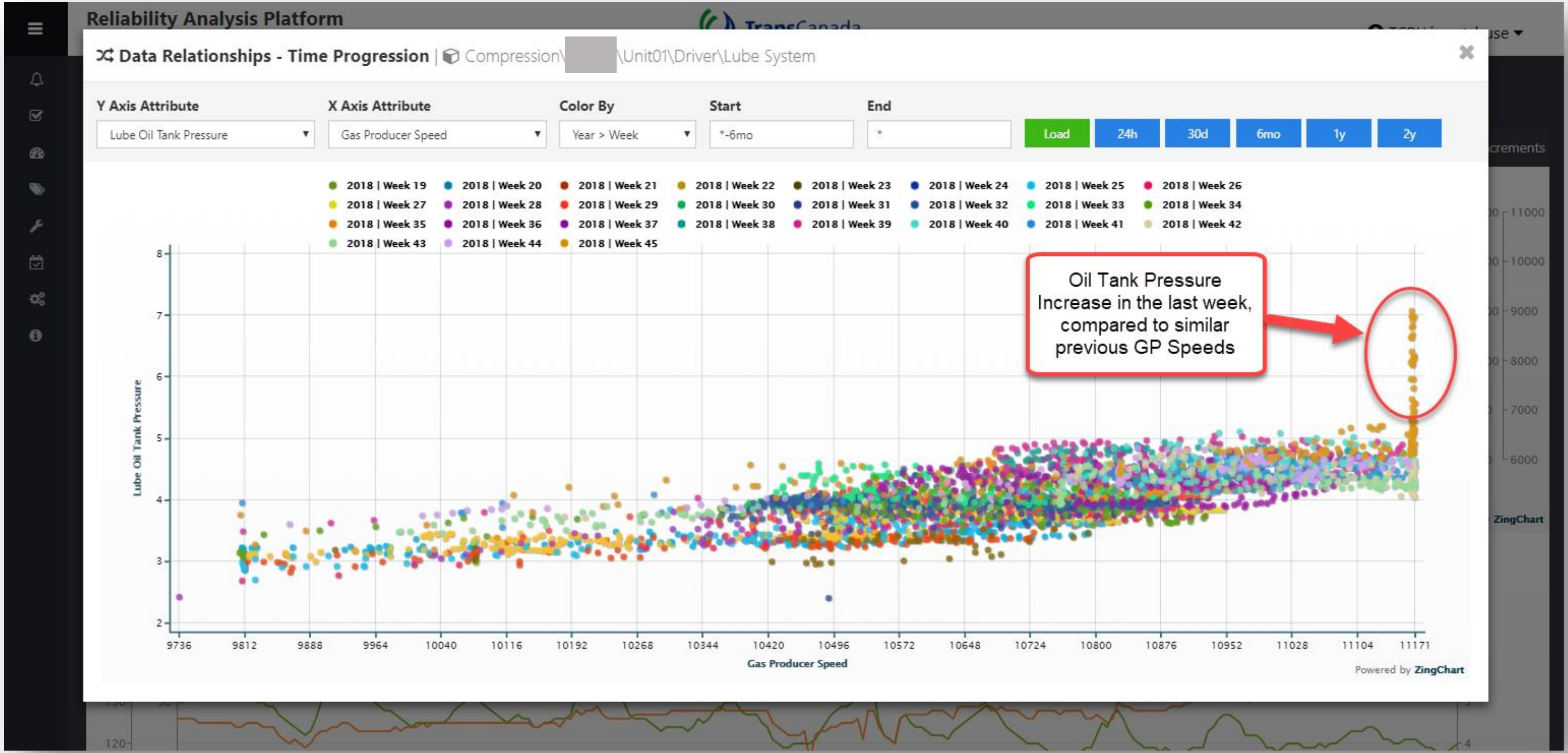

Data Exploration Tools

Conditional Trending



Data Exploration Tools

Bivariate Analysis & Time Progression

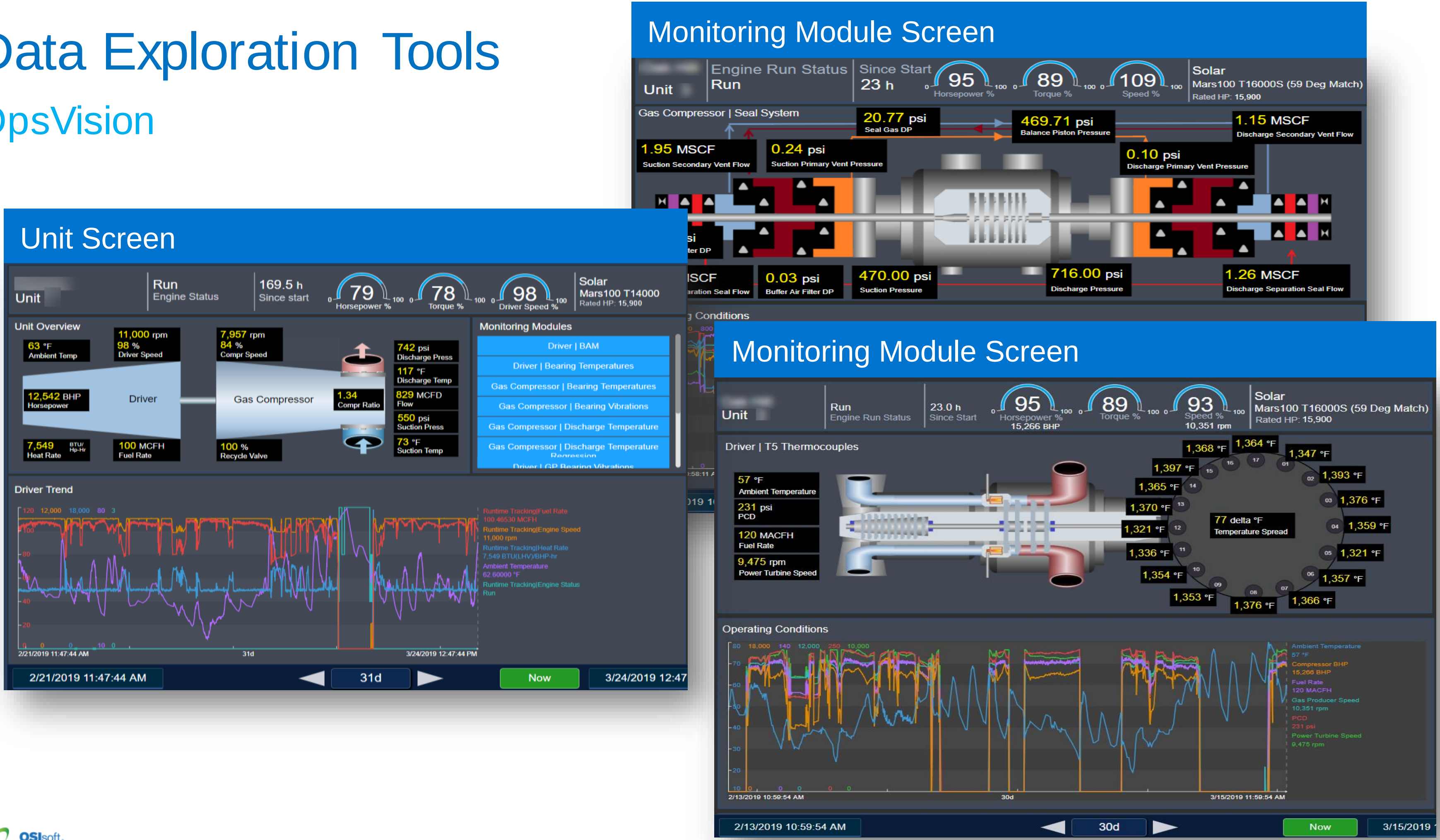


Data Exploration Tools

Fleet Comparison

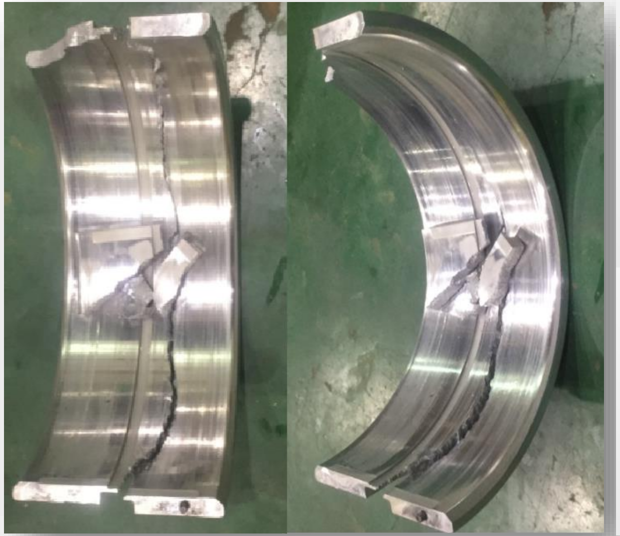
Data Exploration Tools

OpsVision

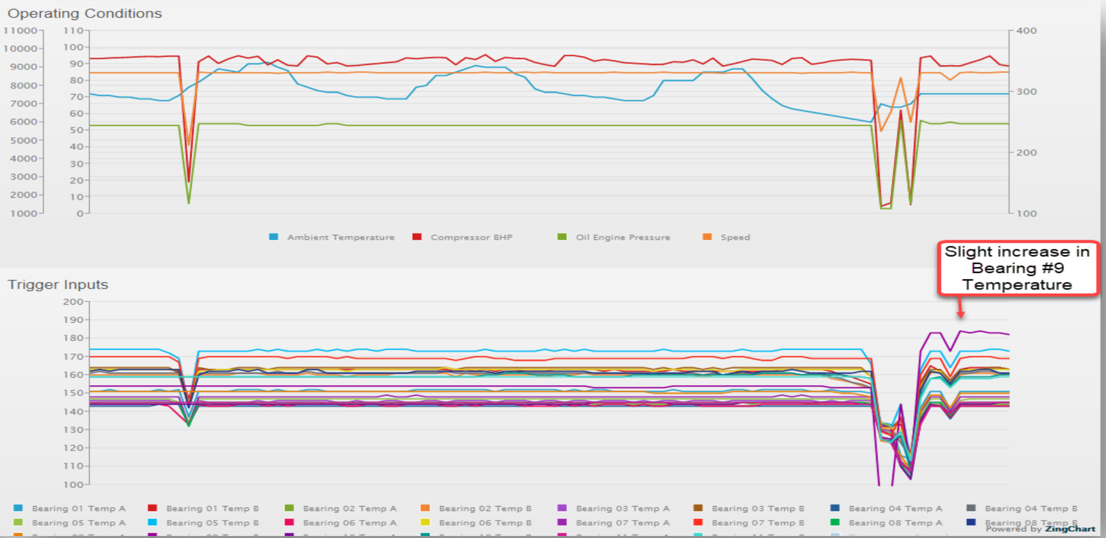


Findings Examples

Engine Bearing Damage



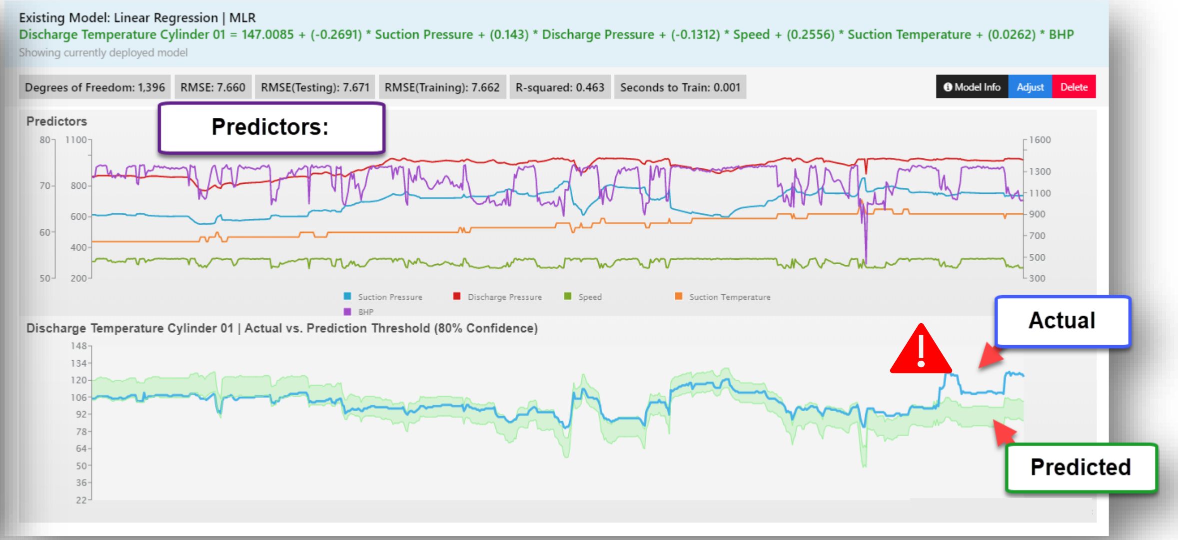
Use SQC to detect abnormal increase in bearing temperature



Findings Examples

Damaged Compressor Valves

Use MLR to detect abnormal increase in discharge temperature



Lessons Learned	Best Practices
Spend time upfront to understand the physical assets and key monitoring areas	Work closely with subject matter experts to understand the asset fleet, key variations, sensor coverage, etc.
No “wrong way” to design AF structure, but some ways work better than others	Use of AF Template Inheritance. Keep size of templates small and avoid tight coupling
More simplistic algorithms deployed at scale are powerful and provide tremendous value	Focus on scalability. Choose simple anomaly detection models first and only increase complexity if accuracy requirements are not met
Data Quality is foundational	Dedicated Tools, Resources and Processes for identifying and managing data quality issues
Detecting anomalies is not enough. Taking corrective actions is the end goal	Accountability centric processes driven by leadership to ensure corrective actions are taken and documented

Future Work

Specific Failure Patterns

Model Management

AWS Integration

Autonomous Retraining

Realtime Condition Monitoring

TC Energy

CHALLENGES

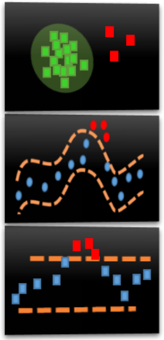
- Realtime Condition Monitoring at large scale
- Diverse Equipment Fleet
- Dynamic Environment

SOLUTION

- Asset Framework: Core of the solution to create digital twins and unify data layer
- Implemented SQC, Regression & Pattern Recognition algorithms
- Minimal custom .NET development for model training, evaluation & data exploration

BENEFITS

- 250+ corrective actions taken in 2019 that mitigated potential significant failures
- Digital asset structure that enables advanced analytics at large scale



Clustering

Regression

SQC

PI Asset Framework

- Core of Solution
- Digital Twin Creation
- Unified Data Layer

> "The PI System in tandem with scalable Machine Learning algorithms has allowed for significant advancement in predicting potential failures, reducing operations and maintenance cost through planned work, while minimizing customer/shipper impacts."
>
> Keary Rogers, Manager, Core Reliability, TC Energy USGO

Pattern Recognition & Linear Regression

- Ionut Buse
- Team Leader, Enterprise Analytics
- TC Energy
- ionut_buse@tcenergy.com

Questions?

Please wait for the **microphone**

State your **name & company**

Save the Date...

AMSTERDAM

October 26-29, 2020

OSIsoft PI World

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DANKON TANK TAPADH LEAT

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TEŞEKKÜR EDERIM

ТИ БЛАГОДАРАМ

DANK JE ΕΥΧΑΡΙΣΤΩ GRATIAS TIBI

ДЗЯКУЙ

GRAZIE

TAK DANKE

AČIŪ SALAMAT MAHALO IĀ ʻOE TAKK SKAL DU HA

DI OU MÈSI

RAHMAT MERCI

GRAZZI ÞAKKA ÞÉR

FALEMINDERIT

ありがとうございました

ĎAKUJEM

HATUR NUHUN

РАХМАТ САҒА

SIPAS JI WERE TERIMA KASIH

MATUR NUWUN

CẢM ƠN BẠN

UA TSAUG RAU KOJ

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