Industrial Analytics: Condition Monitoring of Wind Turbines and Preventative Maintenance Using JMP

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SAIT

Acknowledgments

CFREF

(Canada First Research Excellent Fund)

For providing resources to research industrial data analytics.

EDP Renewable Energy Wind Farm, Spain

For making the operational wind turbine data freely available as open-data for research and education.

Statistical Discovery.™ From SAS.

For designing this great software.

Agenda

- **Scope of Industrial Analytics**
- **Using Process Analysis Techniques for Industrial Equipment**
- **Preparing and Understanding Dataset**
- **Defining Sub-Components Using Physical Laws**
- **Monitoring Degradation/Performance**

Industrial Analytics – Scope and Definition

Large time-series data produced by sensors (IoT) used for Process Optimization, Knowledge Discovery and Decision Making.

Examples:

- Industrial Equipment / Wind Turbines / Solar Panels / Lithium Batteries / Hydrogen Fuel Cells
- Combustion Processes (Gas Turbine/Diesel Engine)
- Air and Water Pollution (e.g., Mining Operations)

Objectives:

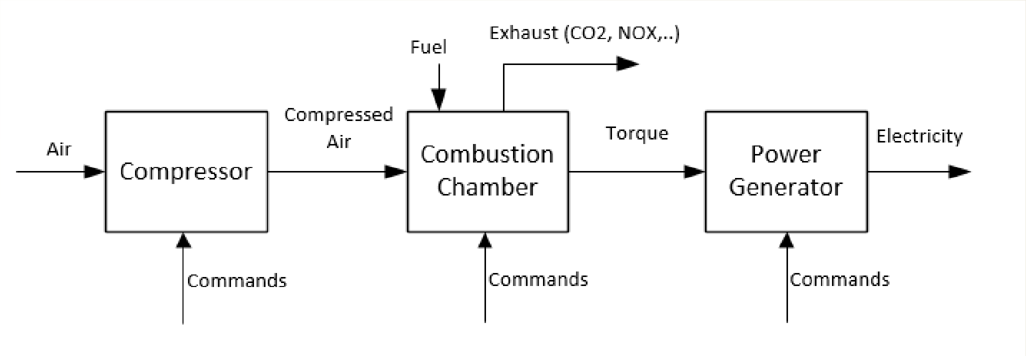
- Prediction of Outcome
  - Electricity, Air pollution (NOx, CO_2, PM2.5)
- Condition Monitoring
  - Monitoring degradation
- Optimizing Operations
  - Reducing pollution, fuel use
  - Increasing produced electricity, …

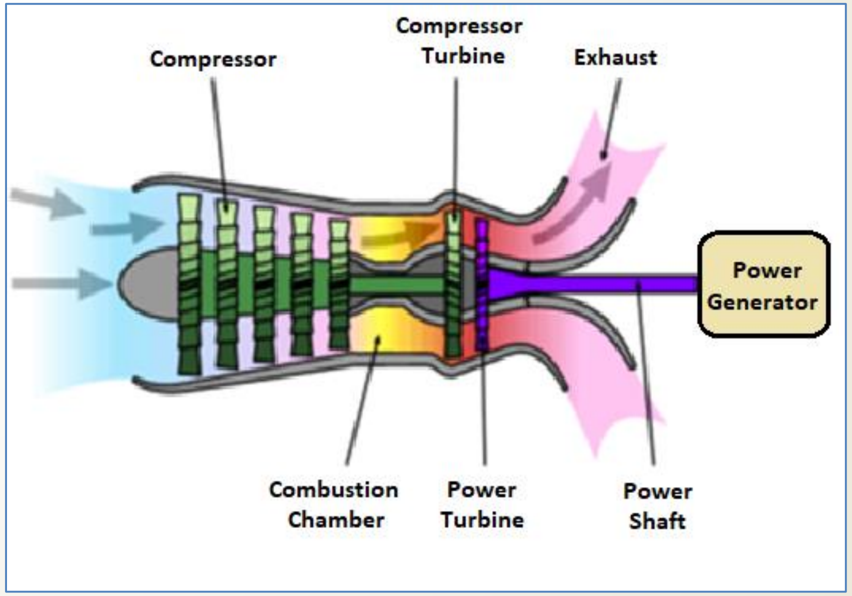
Industrial Analytics – Process Perspective

An industrial equipment is a process with a number of inputs and outputs

Process Definition:

- Industrial Equipment are made of sub-components
- Prediction modeling and condition monitoring is more successful on smaller sub-components



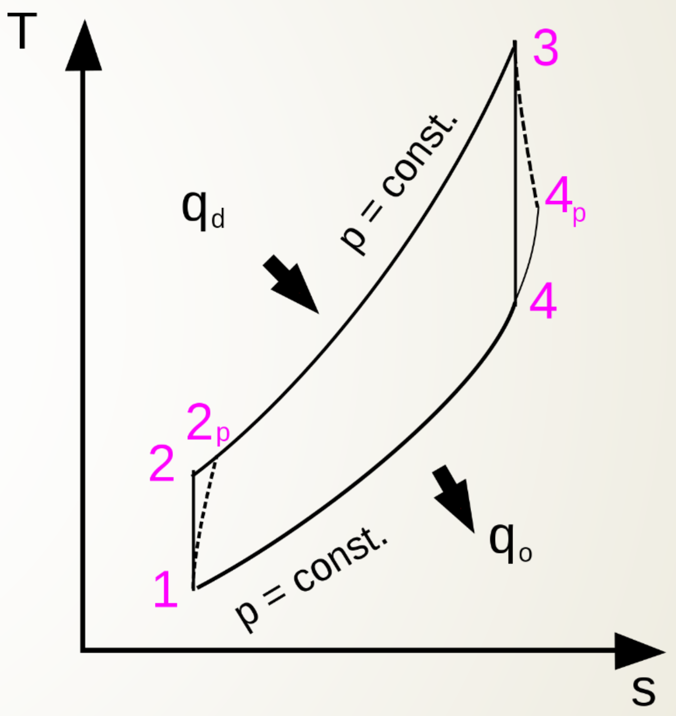


Industrial Analytics – First Principle Thinking

“the first basis from which a thing is known”   Aristotle

First Principles in Industrial Analytics:

- Detect the first principles, until cannot be deducted anymore
- Find the constant performance ratios, that may degrade over time and under different situations **(Operating Modes)**



Take Away:

- Process monitoring techniques can be used for monitoring equipment
- Stochastically monitor execution of the subcomponent over time and similar operating modes

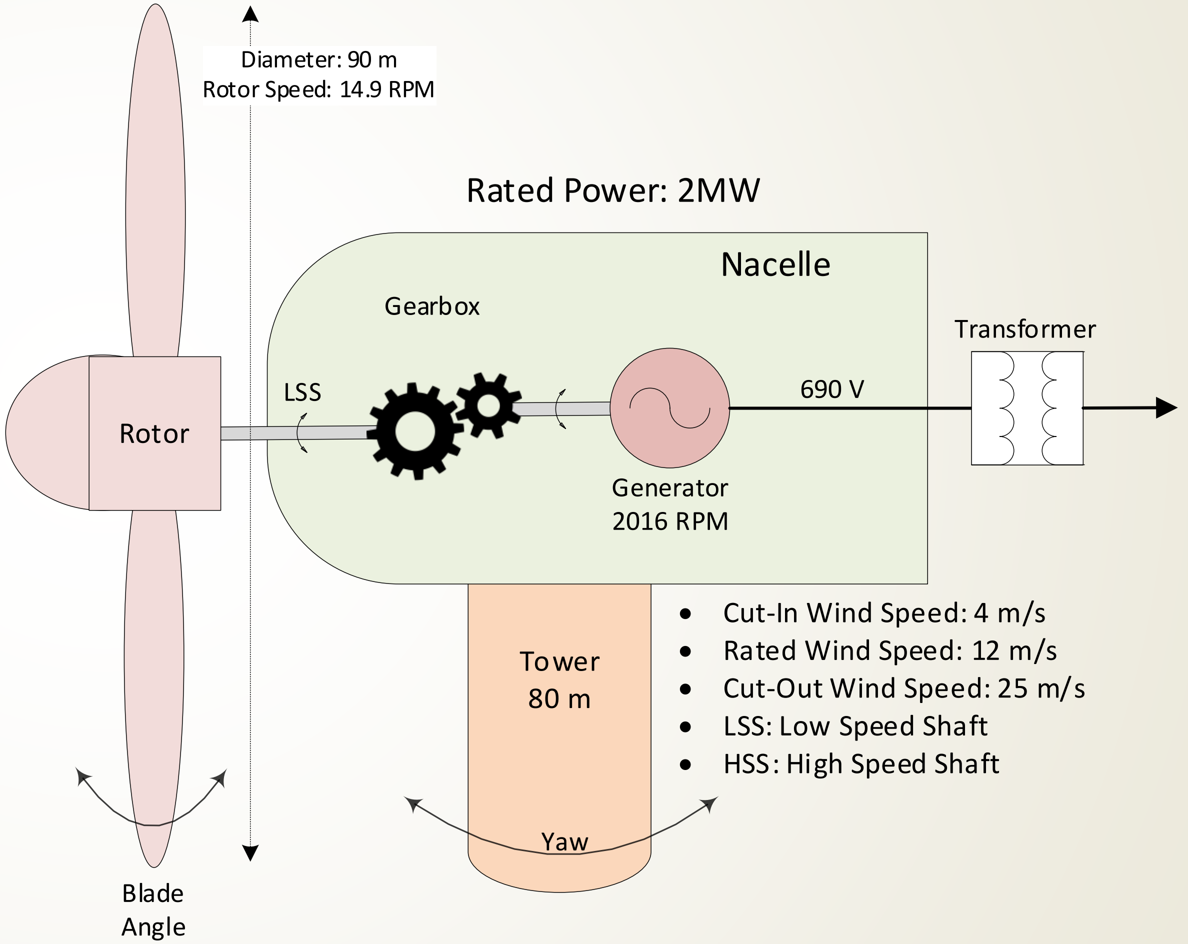
Understanding the Wind Turbine Process

Identifying Main Components:

- Rotor
- Gearbox
- Generator
- Nacelle
- Transformer to grid connection

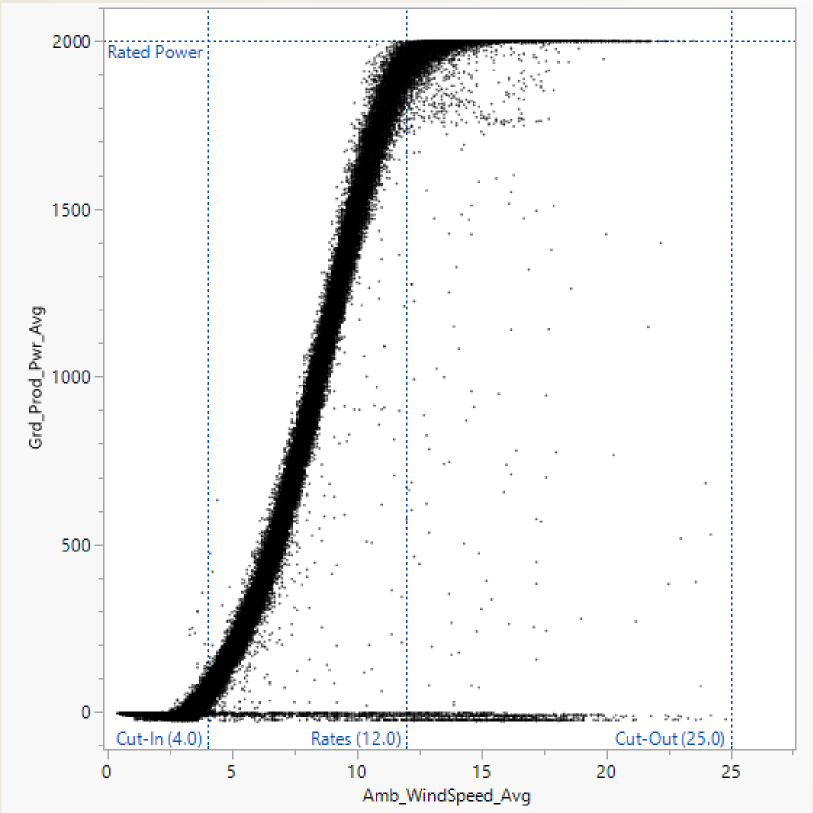
Complex Component Monitoring:

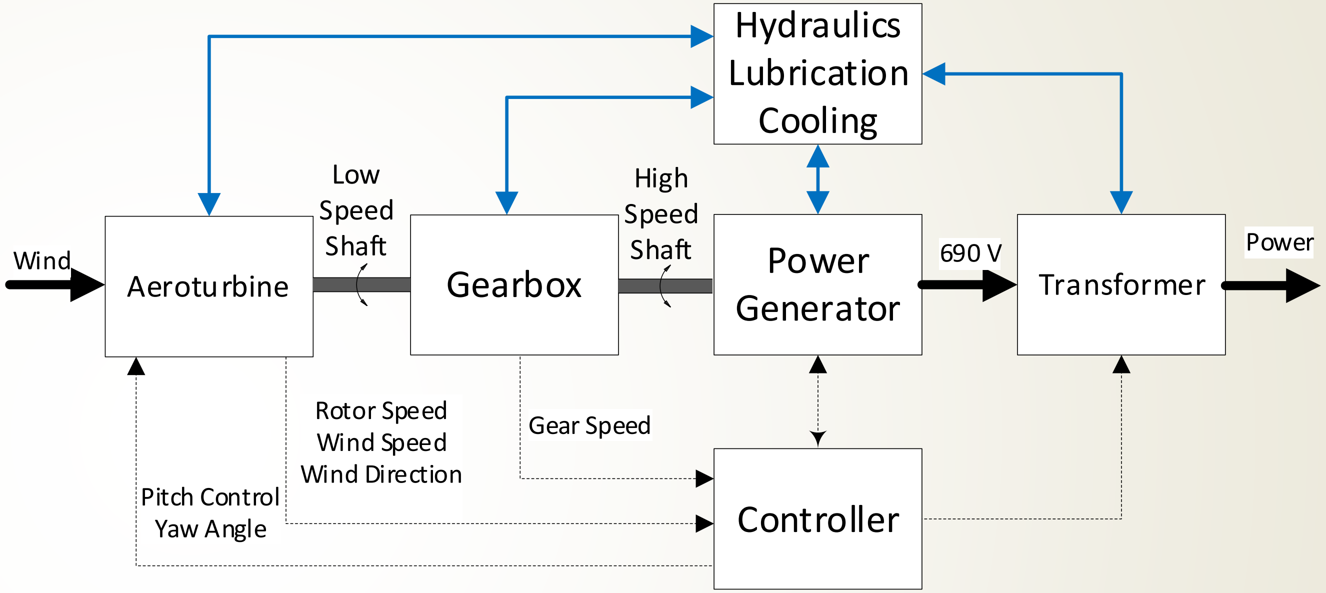
- Components with internal control systems, feedback loops
- Monitoring historical performance
- Modeling using techniques such as Neural Network or KNN (K-Nearest-Neighbor)



Condition Monitoring of a Complex System (Wind Turbine)

- Power Curve displays:
  - produced power (output)
  - wind speed (input)
- Live Demo

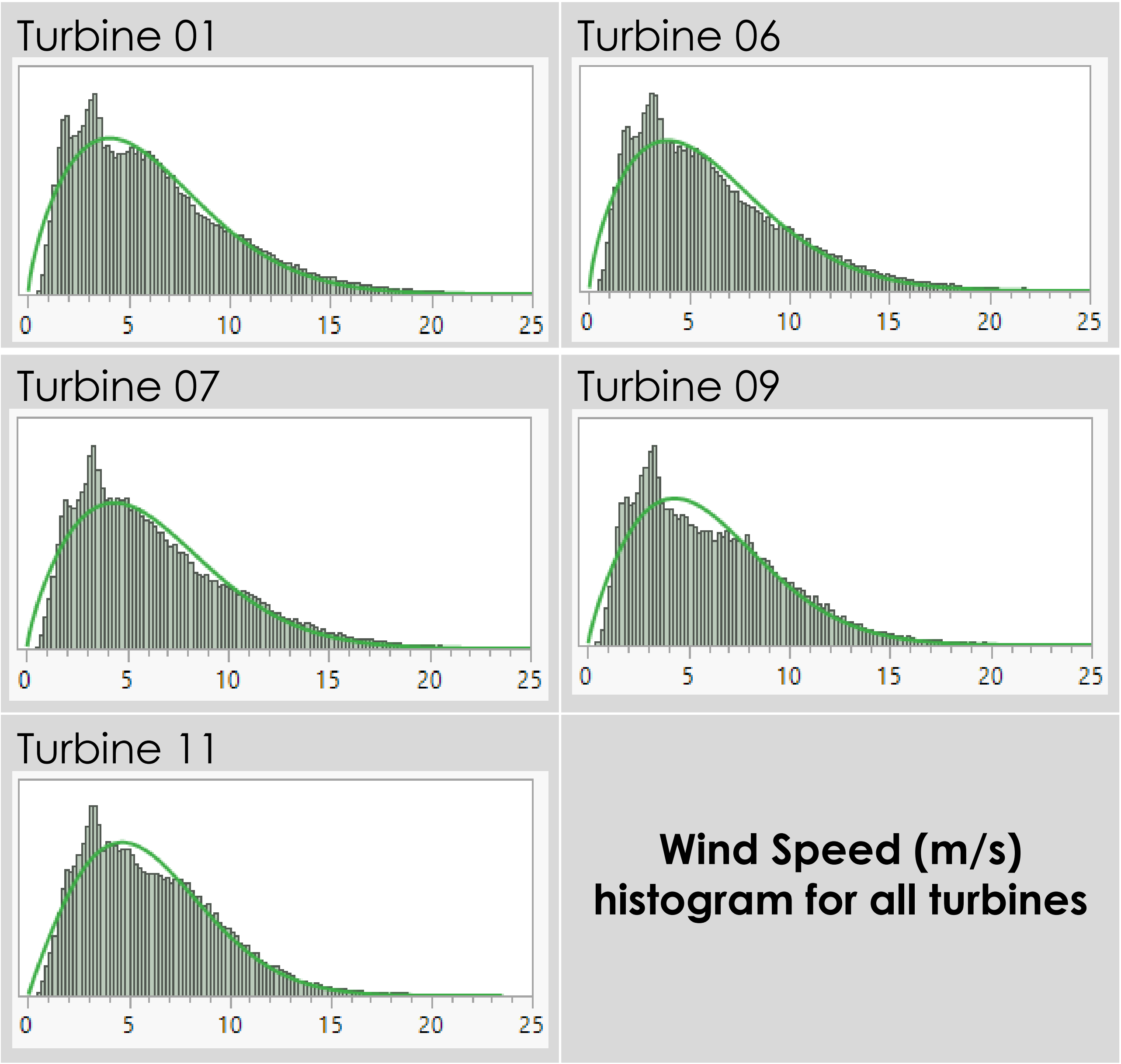




- A complex industrial system is built of multiple components
- Each component has interaction with others and follows a simpler logic
- Condition monitoring of a specific component is more successful than the whole system

Univariate Analysis of Process Parameters (Wind Speed)

- **Validating data quality by comparing against physical laws**
- **Wind speed usually conforms to Weibull distribution**
- **The plots against Weibull indicate distortions exist, which could be due to blade movements or interaction (wake) effect of turbines**
- **Each non-conformance may offer an improvement opportunity**



Wind Speed (m/s) histogram for all turbines

Preprocessing

Missing Values

- Are zeroes actual 0 or missing value?
- Analyze patterns of missing values

Outliers

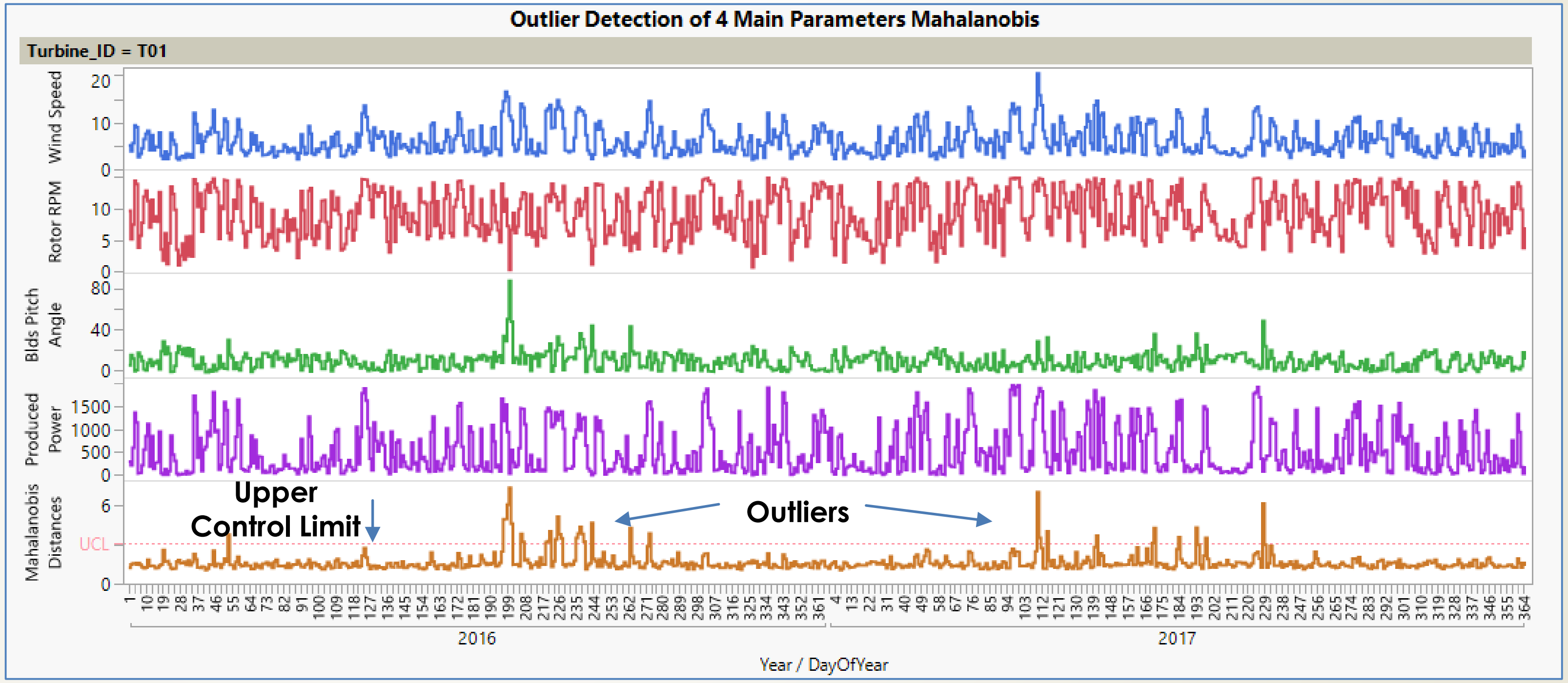
- Remove any value physically not possible
- Avoid changing values to “what they should be”

Date/Time Conversions

- Creating calculated fields to fit JMP format
- Creating units of time (e.g. day of process)

Caution: Modifying data values
Sensory data may contain anomalies of interest which extreme manipulations based on human judgment may remove them

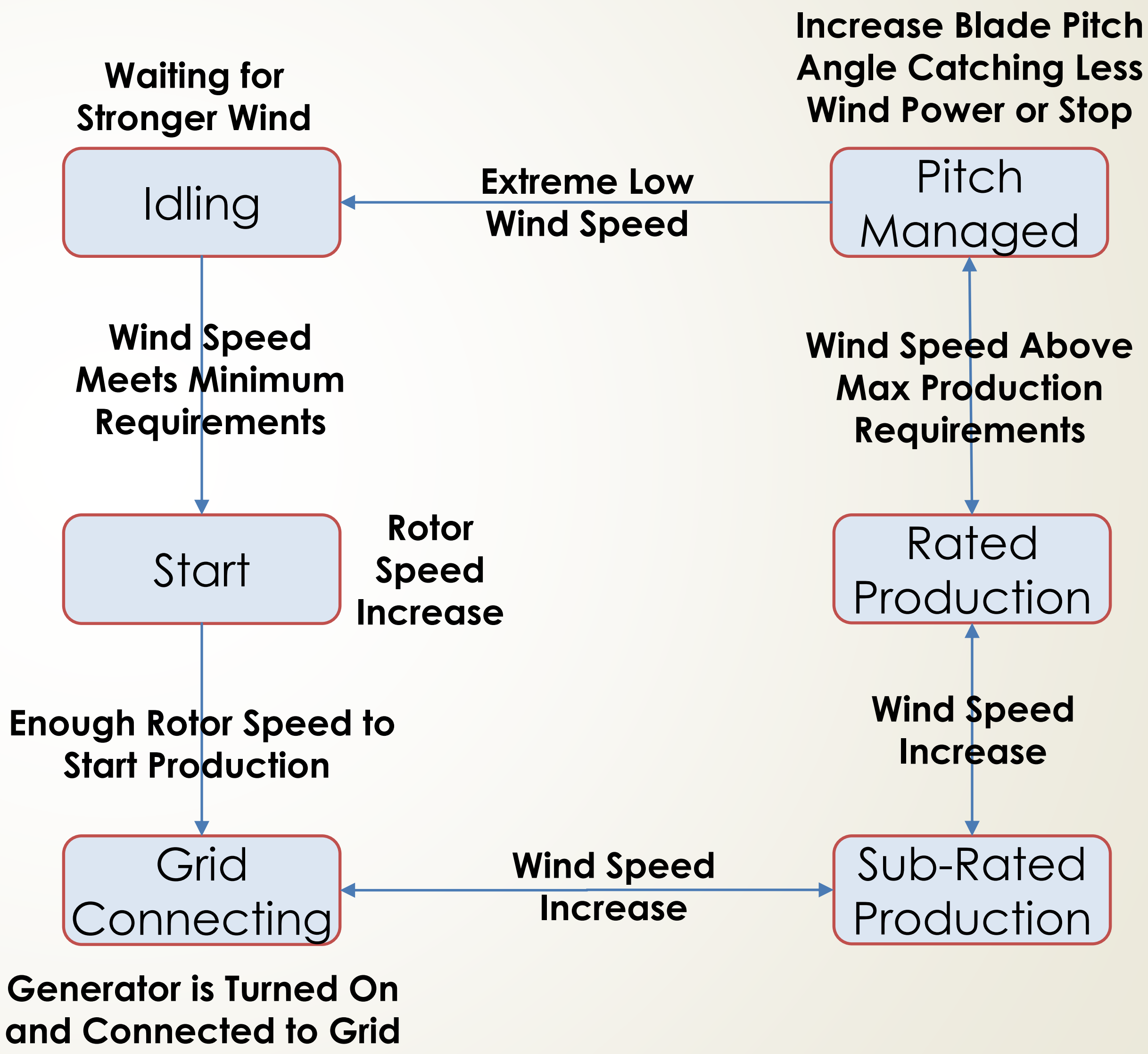
Multivariate outliers are indication of abnormal situations or equipment misalignment / degradation



Live Demo

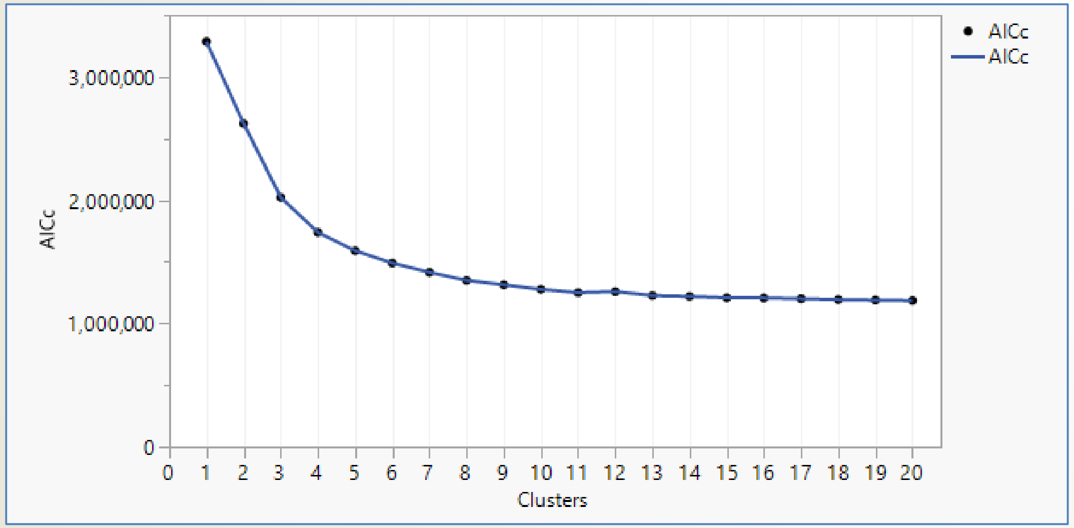
Wind Turbine Operational Modes (Over-Simplified)

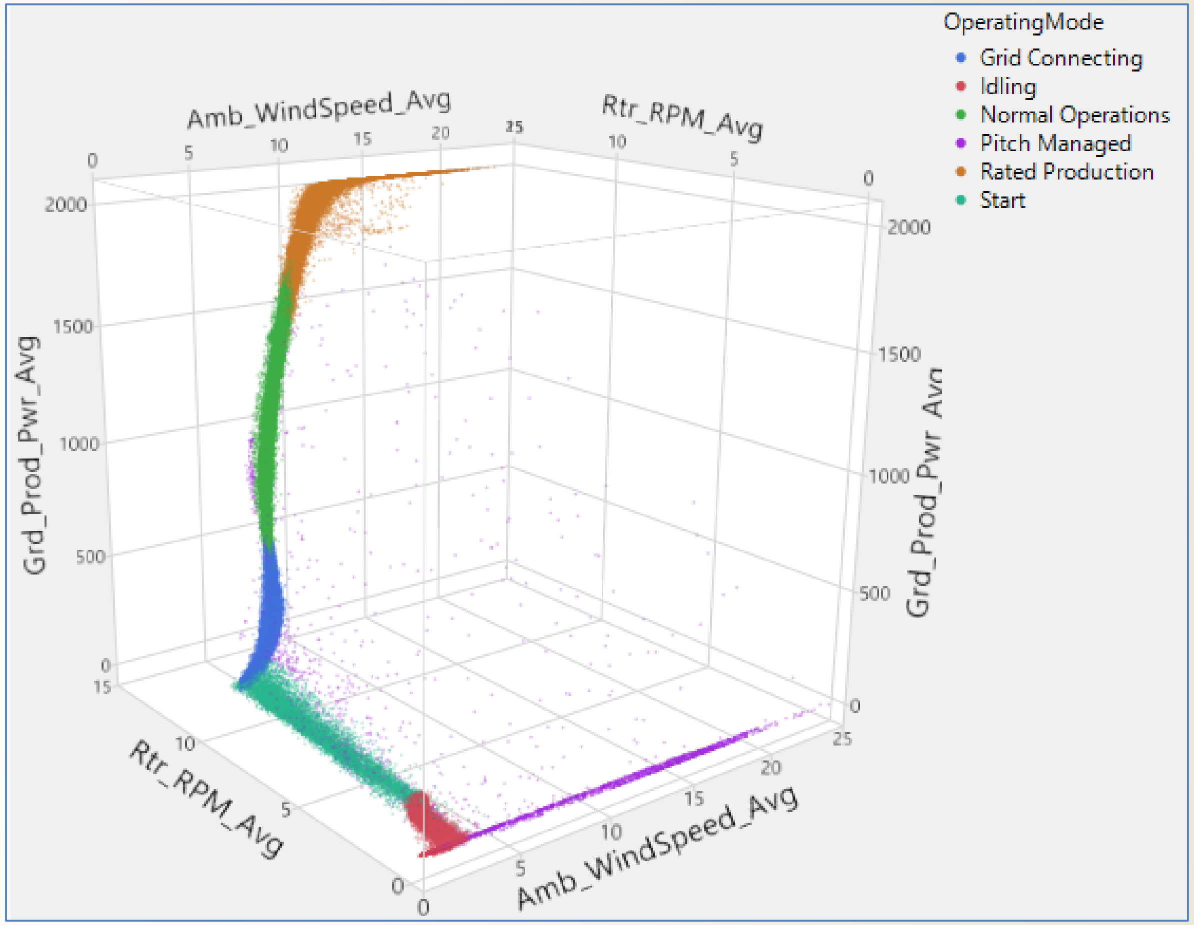
- Using modern big data analytics as a complement of traditional methods
- Objective is visualization of operational status
- Finding minimum parameters describing the process and operating modes
  - Wind Speed
  - Power Generated
  - Rotor Speed
  - Blade Pitch Angle



Identification of Operational Modes (Clustering)

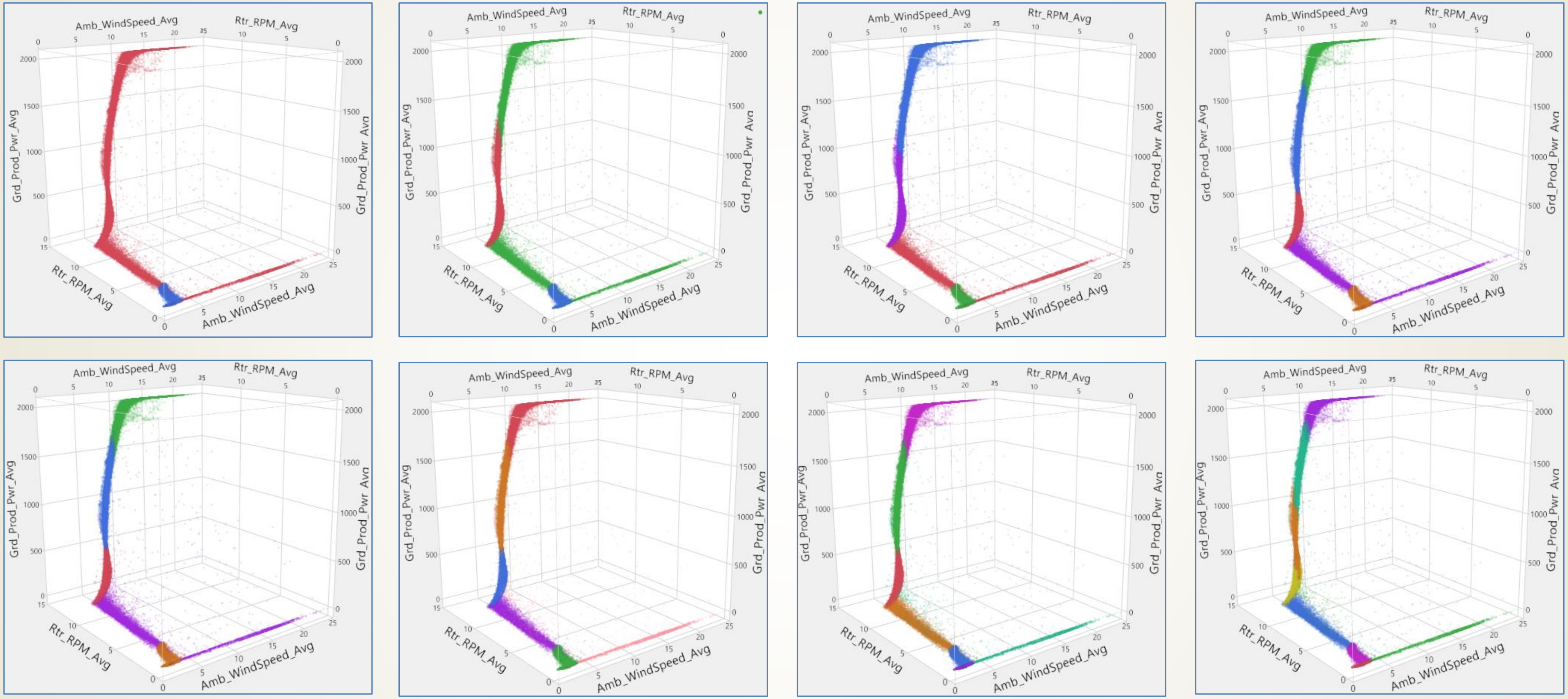
- Selected 6 operating modes (clusters)
  - AIC slope becoming flat after 6 clusters
  - Selecting minimum number of clusters where the gain in accuracy is slowing
  - Selecting too high number of clusters is overfitting
  - Number of clusters must match operating procedures





- Live Demo
  - Clustering
  - Comparing AIC

Identification of Operational Modes (Clustering)



Live Demo

Identification of Operational Modes (Clustering)

- Industrial processes operate with multiple operational modes
  - Rated / Sub-Rated Production
  - Pitch Managed / Idling / Connecting / Start

Used Normal Mixture clustering

- Assumes each cluster has multivariate normal distribution
  - Clusters can overlap
  - Clusters are convex
  - There is one high peak

Hierarchical
- Used for larger data sets
- Gives exact clustering logic

K-Mean
- Computationally intensive
- Finds nearest cluster center

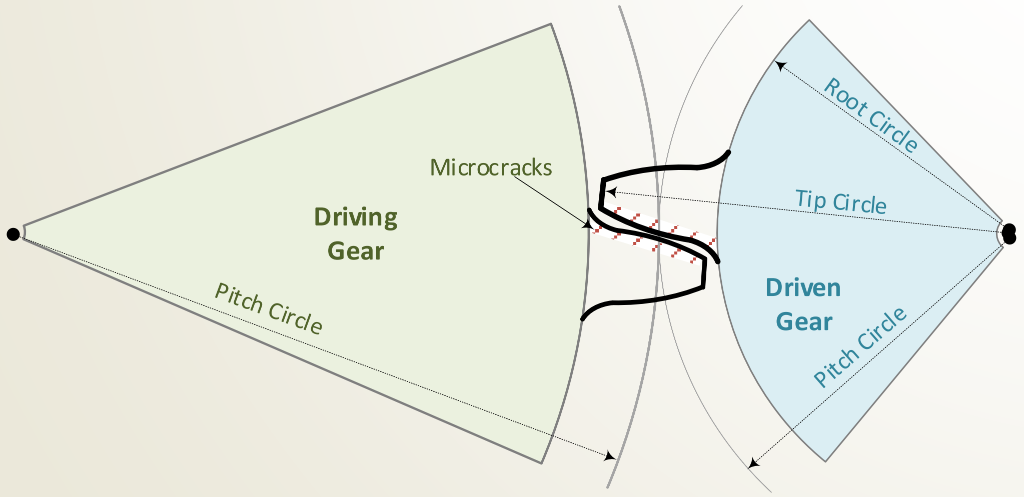
Normal Mixture
- Relatively fast
- Multivariate Normal Distribution clusters

		Turbine_ID											
		T01											
		Amb_WindSpeed_Avg			Rtr_RPM_Avg			Blds_PitchAngle_Avg			Grd_Prod_Pwr_Avg		
OperatingMode	N	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
Grid Connecting	29548.0	3.1	6.8	5.2	10.5	13.3	11.5	-2.3	0.8	-1.1	-0.9	579.2	223.9
Idling	26767.0	0.4	4.6	2.1	0.0	4.3	0.8	23.6	24.3	24.0	-25.0	0.9	-5.7
Pitch Managed	3094.0	0.6	24.8	8.6	0.0	14.9	2.6	-2.2	90.6	65.6	-30.1	1803.9	84.8
Rated Production	13958.0	9.2	23.5	12.7	14.3	14.9	14.8	-2.0	22.8	4.2	1322.2	2000.5	1870.1
Start	8323.0	1.7	5.0	3.4	0.0	11.5	7.1	-0.4	36.4	11.0	-27.5	122.0	11.4
Sub-Rated Production	22993.0	5.6	10.6	8.2	11.8	14.9	14.0	-2.5	-0.4	-1.9	91.0	1710.3	923.1

Condition Based Monitoring

1. On operating modes which highlight the parameter monitored
2. Exclude parameter from interferences such as "Set-Points" or external controls
3. Follow laws of physics, ratios, aerodynamics, thermodynamics, …

Performance Based	• Ratio Monitoring (Gear/Compression) • Compression Ratio Monitoring
Non-Performance Based	• Lubricant Testing • Vibration Monitoring
Direct Monitoring	• X-Ray Gearbox/Pipeline • Corrosion/Erosion Measurements

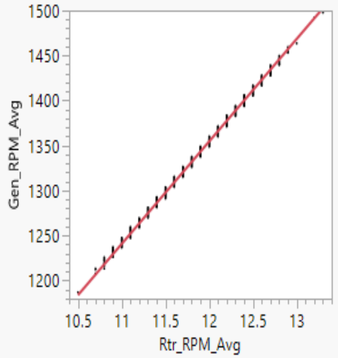


- Build a base line model of healthy condition
- Monitoring on-going
- Gearbox: simple linear regression

Linear Regression of Gear Teeth Ratio

Response Gen_RPM_Avg Turbine_ID=T01, OperatingMode=Grid Connecting

Regression Plot

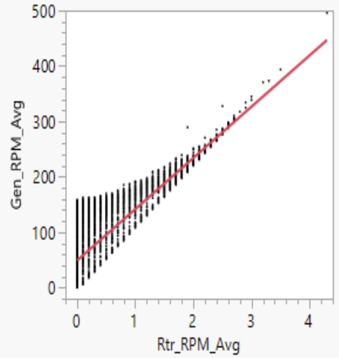


Summary of Fit

RSquare	0.996526
RSquare Adj	0.996526
Root Mean Square Error	3.194585
Mean of Response	1298.875
Observations (or Sum Wgts)	29548

Response Gen_RPM_Avg Turbine_ID=T01, OperatingMode=Idling

Regression Plot



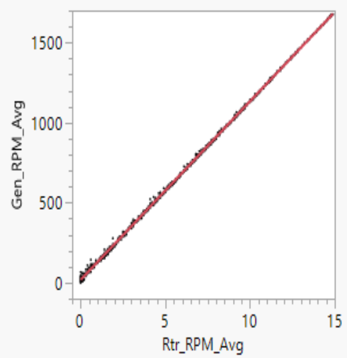
Summary of Fit

RSquare	0.835177
RSquare Adj	0.83517
Root Mean Square Error	39.06795
Mean of Response	124.2414
Observations (or Sum Wgts)	26767

Not Included in Analysis

Response Gen_RPM_Avg Turbine_ID=T01, OperatingMode=Pitch Managed

Regression Plot

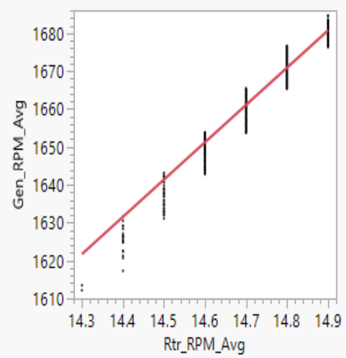


Summary of Fit

RSquare	0.999388
RSquare Adj	0.999388
Root Mean Square Error	11.74104
Mean of Response	305.8564
Observations (or Sum Wgts)	3094

Response Gen_RPM_Avg Turbine_ID=T01, OperatingMode=Rated Production

Regression Plot



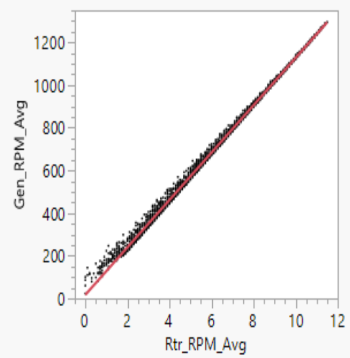
Summary of Fit

RSquare	0.92214
RSquare Adj	0.922135
Root Mean Square Error	2.30247
Mean of Response	1675.505
Observations (or Sum Wgts)	13958

Not Included in Analysis

Response Gen_RPM_Avg Turbine_ID=T01, OperatingMode=Start

Regression Plot

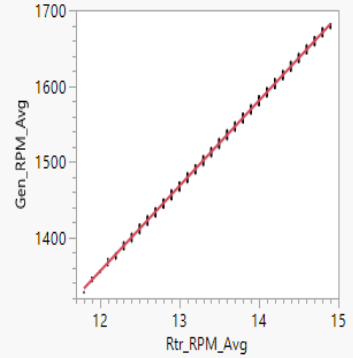


Summary of Fit

RSquare	0.998559
RSquare Adj	0.998559
Root Mean Square Error	11.36642
Mean of Response	809.4769
Observations (or Sum Wgts)	8323

Response Gen_RPM_Avg Turbine_ID=T01, OperatingMode=Sub-Rated Production

Regression Plot



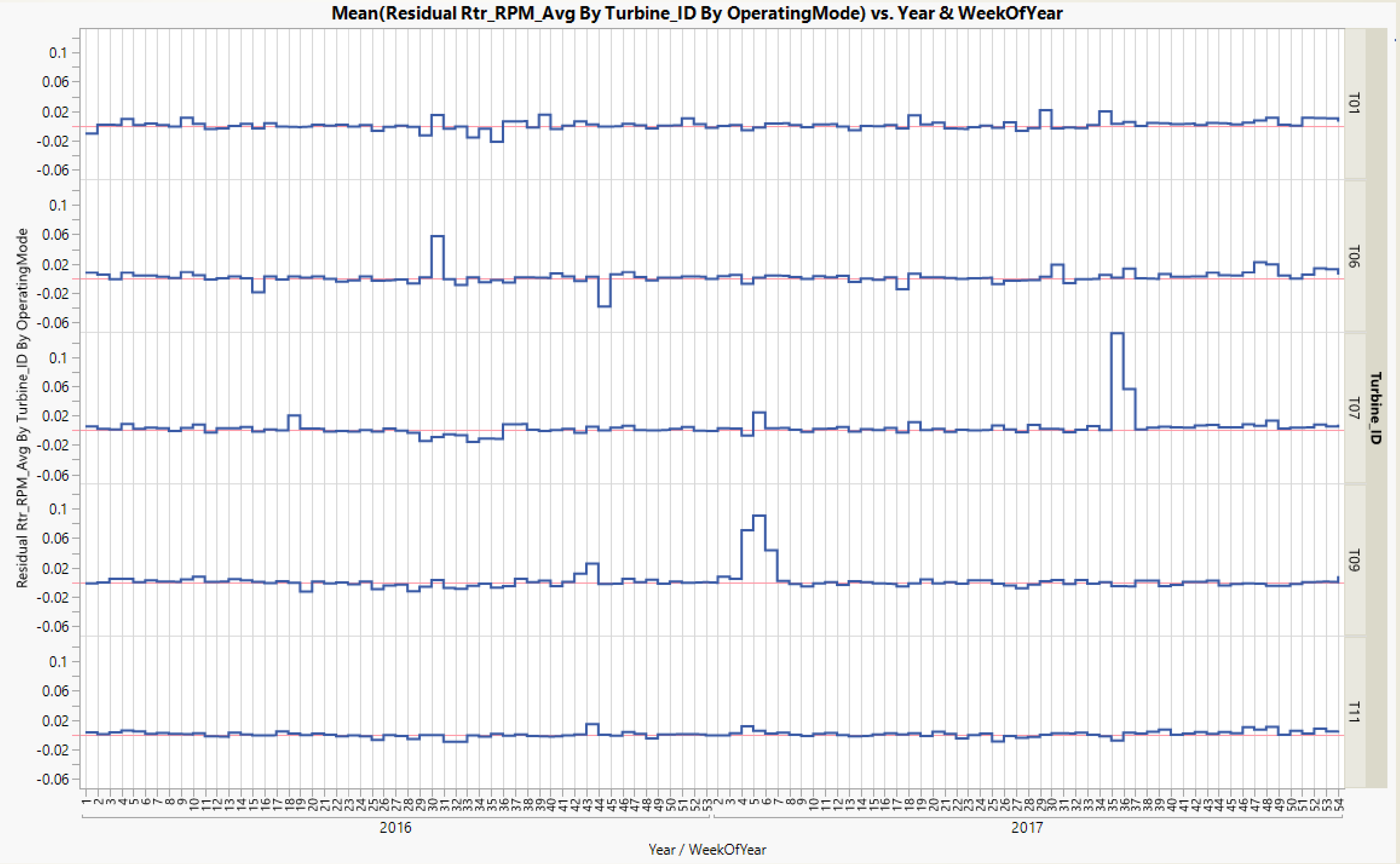
Summary of Fit

RSquare	0.998037
RSquare Adj	0.998037
Root Mean Square Error	3.265853
Mean of Response	1575.947
Observations (or Sum Wgts)	22993

- Selecting the higher R^2 operating modes for inclusion in final analysis
- Live Demo

Detection of Mean Ratio Change (Wear)

- Mean can be interpreted as wear changing the gear ratio
- Due to higher pressure on smaller gear, more wear happens typically on smaller gear, increasing ration (upward trends)
- Live Demo



The trends are a monitoring tool for engineers and exact interference time is decided by the personnel.

Summary

- A complex process has multiple operating modes
- Each operating mode highlight a portion of the operational process
- Clustering methods can be used for isolation of the operating modes
- Condition monitoring using operating modes for detecting degradation
- Monitoring sub-components with considerations to physical laws
- Monitoring complex systems based on historical performance