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Wind Turbine Reliability Database Update

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Abstract

This report documents the status of the Sandia National Laboratories' Wind Plant Reliability Database. Included in this report are updates on the form and contents of the Database, which stems from a five-step process of data partnerships, data definition and transfer, data formatting and normalization, analysis, and reporting. Selected observations are also reported.

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Introduction

The goal of Sandia's Wind Plant Reliability Database and Analysis Program is to characterize the reliability performance of the US fleet to serve as a basis for improved reliability and increased availability of turbines. The Wind Plant Reliability Database and Analysis Program is designed to fill a need identified by wind plant owners and operators to better understand wind turbine component failures so efforts can be focused to resolve these failures and /or mitigate the consequences, resulting in improved operations and reduced maintenance costs. With sufficient participation across the fleet, benchmarking of fleet-wide reliability performance will characterize the industry as a whole. Characterization of reliability issues will help prioritize and facilitate R&D efforts to foster component and system design improvements. Together these actions are aimed at reducing financial and technical risks for a growing wind energy market.

Sandia has historically been engaged in system reliability research activities in safety, materials, and fatigue. The broad-based expertise and capabilities that evolved from this engineering of numerous critical systems is now being applied to wind energy systems. For example, wind turbines have mission requirements of high reliability to perform under specified conditions for established durations of time. Failures, events, repairs, and replacements will all have impacts on turbine and plant availability, and cost of operation.

A national vision of 20% of electrical demand supplied by wind energy (cite the 20% energy plan) has been published by the Department of Energy (DOE). To accomplish a market penetration of this magnitude the following must occur:

- Wind turbines must be an economically competitive technology
- Risks to reliable plant performance must be manageable
- The technology must have strong public acceptance based on proven performance
- Policies that promote renewable energy must be put in place and maintained

Plant availability is a key metric of performance for wind plants as it is directly related to energy production and revenues. Energy is not generated while components are being repaired or replaced. Although a single failure of a critical component stops production from only one turbine, such losses can add up to significant sums of lost revenue. An availability increase will improve economics, reduce risks, and provide relevant contributions toward meeting 20% penetration goals. An improvement in overall fleet availability performance of 1 percentage point will result in an additional 12,000,000 MWH for the US and $600 M in additional revenue for operators, at 20% wind penetration.

The consequences of real or perceived reliability problems extend beyond the direct cost to the plant owners. Long-term loans are used to finance power plants that are heavy with upfront capital costs such as wind plants. Financial institutions assess the risk of investing in wind energy and set interest rates accordingly. Reducing the risk of unpredictable or unreliable performance improves the ability to finance projects. As financial institutions gain confidence in wind power, insurance and financing costs could decrease, thus increasing the competitiveness and use of wind energy.

Objectives of the Wind Plant Reliability Database and Analysis Program

The goals of any wind plant reliability program are to improve availability, reduce costs of Operations and Maintenance (O&M), and maintain high levels of production.

To help wind plants reach these goals, the Wind Plant Reliability Database and Analysis Program has a mission to c*haracterize* reliability performance issues and *identify* opportunities for improving reliability and availability performance of the national wind energy infrastructure.

The following program objectives will help move the industry toward improved reliability:

- Guide DOE program Research and Development (R&D) investment through identification of critical issues, including determination of relative impact of component failures
- Provide data for root cause analyses of component failures
- Establish national benchmarks for reliability
- Guide industry actions for improved equipment performance and operating practices
- Provide data partners with benchmarking of their own equipment against national benchmarks
- Give specific feedback assessments to partners: operators, owners, asset managers, and equipment suppliers
- Identify components that result in highest cost, highest downtimes, and/or lowest availability, and which would be the best candidates for revised O&M practices, or other types of improvement
- Facilitate a culture change in wind plant operation to more effectively monitor and utilize reliability information

Part of the Program's goal is to help increase availability through well understood and numerically characterized reliability performance of component and systems. Reliability analysis is for the purposes of efficient planning. In this case, planning will include understanding failure rates, forestalling failures, managing efficient repairs and replacements, and having optimum spares inventory. Individualized reliability reports for each data partners will contribute to efficient planning. Published reports of aggregated reliability statistics of the US fleet, when sufficient numbers are included, will provide benchmarks of reliability performance and also trend reliability improvements over time.

Program Activities from Inception through FY08

Since the inception of the Wind Plant Reliability Database and Analysis Program, a number of actions have been undertaken to help meet the above objectives, including structuring the necessary industry collaborations and creating a process to collect, analyze, identify, and disseminate critical failure modes and areas for improvements in system reliability. Activities to date include:

- Two Wind Turbine Reliability Workshops with industry (2006, 2007)
- Background O&M investigations at selected wind plant sites
- Publication of ***Wind Turbine Reliability: Understanding and Minimizing Wind Turbine Operation and Maintenance Costs,*** Sand2006-1100
- Publication of ***Wind Turbine Reliability: A Database and Analysis Approach***, Sand2008-0983

- Development of the National Reliability Database
- A survey conducted on blade reliability, with results reported at Sandia's Blade Workshop in June 2008
- Non-disclosure agreements (NDAs) signed with over a half dozen parties
- Development of a reporting template for use with individualized data reports
- Development of a Wind turbine taxonomy (component breakdown)

The National Reliability Database

Many industries, including fossil fueled power generation, have established anonymous databases that serve to benchmark their reliability and performance, giving operators both the ability to recognize a drop in reliability and the data they need to determine the source of low reliability. In mature industries, O&M management tools are available to help maximize maintenance efficiency. Achieving this efficiency is a key factor in minimizing the cost of energy (COE) and maximizing the life of wind plants, thereby increasing investor confidence.

The backbone of the Wind Plant Reliability Database and Analysis Program is the National Reliability Database, which houses the data used to develop the statistics and analytical reports. The database uses a Structured Query Language (SQL) server, housed on computing resources owned by Sandia National Laboratories. This option offers cost effective data security with the firewall exemptions necessary for data transfer from partners located outside Sandia.

The database architecture was originally developed by ARES Corporation and is described in SAND 2006-1100 D. This database has been tested with data from an initial partner with operational data transferred to the database. Data from SCADA (Supervisory Control and Data Acquisition) files and work orders comprise the database at this time. (See the section on "Data Definition and Transfer" for more information on these data sources.)

There are five key steps in aggregating diverse industry experience from across the country into summary reports, which supply the fundamental information to achieve program goals. As explained in the following sections, the steps are:

1. Data Partnerships
2. Data Definition and Transfer (what data will be used, how to transfer it, etc.)
3. Data Formatting and Normalization
4. Analysis
5. Reporting and Analysis Output

Data Partnerships

The Wind Plant Reliability Database and Analysis Program is based on the acquisition of operational data to determine basic reliability statistics of wind turbines deployed throughout the United States. It is in the operation of wind plants that reliability data of components are recorded. Outage events, faults, and failures contribute to the unreliability observed in the plant or individual turbines. Other types of reliability-related O&M data include the spare parts and human and equipment resources needed to perform preventative and corrective maintenance. Much of this data resides in plant SCADA systems and work orders.

The process to acquire data from partners requires some effort from the partners. Typically, data partners need to provide electronic or other forms of access to the SCADA and work order systems. Whether electronic or otherwise, SCADA codes, work orders, and operational practices will need to be understood for proper analysis. In exchange for the data, data partners are provided with individual reliability reports. Examples of such reports are provided in the section on “Reporting and Analysis Output” and a full sample report is provided in Appendix B.

Ensuring protection of information is critical for successful partnerships. Sandia and potential wind plant owners and operators prepare, review and sign non-disclosure agreements (NDAs) requiring that neither Sandia nor the data partner will share raw data or analysis results with parties outside the agreement. The process has become somewhat standardized as additional partnerships are formed. The NDA also makes clear that data provided will be used for purposes of aggregation into the US fleet National Reliability Database, but no individual contribution will ever be identified or attributed to a specific wind plant.

Data Definition and Transfer

The data needed is that which contributes to answering the basic questions of **how often** something fails**, how long** is it out of operation, and **how much** the down time costs. In other words, the symptoms, cause, and corrective actions for any failure or maintenance activity need to be determined.

To determine answers to these questions, the following information is required for reliability analysis:

- For each downtime event:
  - Turbine ID: Distinguishes individual turbines
  - Event Code: Unique identifier for type of downtime event
  - Event Name: Descriptive label for type of downtime event
  - Event Type: Type of downtime (e.g., failure, preventative maintenance)
  - Event Cost: Cost per occurrence and/or hour of downtime
- In general:
  - Monitoring period: First and last day the turbine was monitored for downtime events
  - Turbine operating hours: Total time, during the monitoring period, that the turbine was operating (generating)
  - Turbine idle time: Total time, during the monitoring period, that the turbine was capable of operating (i.e., not down for any reason), but was not operating. (Examples of this time include no wind or curtailment)

There are potentially vast amounts of data (billions of data points) and this data differs from wind plant to wind plant. The data needed for reliability comes down to three types – Supervisory Control and Data Acquisition (SCADA), work orders, and summarized data.

SCADA Data

A subset of the data from every turbine’s control system, as well as data collected at the metering, substation, and grid connection interface, is stored in the plant-wide Supervisory Control and Data Acquisition (SCADA) system. When an operator or the control system shuts a turbine down, that shutdown is recorded and stored in the SCADA system. In addition to data capture, SCADA systems can generate reports that summarize monthly outages and power production. These reports may also be part of the data gathered from partners.

There are several ways SCADA data can be transferred to Sandia for input into the National Reliability Database:

- Direct SCADA access (via network connection to the SCADA system) where systems will be set up and maintain the connection to get this data. This method of data transfer will require interaction with data partner staff to set up the connection.
- Web access, if the SCADA has a web-based client that Sandia staff can access.
- Transfer of data by data partner staff, using an acceptable electronic format (including comma separated value (CSV), MS Excel spreadsheets, SQL database output, and any other format that can be easily transferred into a SQL database). Transfer can be accomplished via e-mail, CD/DVD, or FTP.

Work Order Data

Work orders are often generated by plant mangers to capture the need for repairs or other types of maintenance. A work order may have multiple purposes. It may be used for tracking of human resources, or for tracking the time the turbine spent offline. For purposes of reliability tracking, work orders may document the investigation into the cause of outage and which component failed and/or was replaced. In this way, work orders may provide insight into turbine performance and document operator actions which indicate the root cause of failure.

Work orders can be used for normal preventative maintenance. Scheduled maintenance activities, which may not be recorded in the SCADA system, will be identified by work orders. It is important to account for these actions as they contribute to turbine unavailability, in the strictest sense. Ideally, work order systems will be computerized in an automated maintenance management system.

Currently, both SCADA and work orders are being used for input into the National Reliability Database and for analysis. These two sources provide raw data. Transferring raw data ensures that Sandia is responsible for the assumptions used to summarize the data – leading to a standardized and uniform approach in creating a baseline and benchmarking the industry. With the lower level of detail offered by raw data, many types of analysis become possible, including exploring variability within a farm, comparing turbines, exploring trends and correlation with greater detail (ex: hourly vs. monthly), exploring lost opportunity costs of downtime (in terms of generation kW and/or dollars), and exploring the wind's impact on generation and downtime.

If electronic work orders are not available, data partners provide copies of paper work orders to Sandia. However, work order information available electronically is greatly preferred and facilitates timely reports back to the data partner.

Summarized Data

Summarized data includes monthly or annual operating reports, survey data, or other types of downtime and maintenance event information not reported through SCADA or Work Orders. Examples could include fault and failure logs, outage reports, parts consumption histories, etc. Having less data to transfer and store is a benefit of obtaining summarized data. Another feature is that it shifts the data summarizing to the operator or data partner. However, when less detail is provided, detailed analysis will be more limited. For purposes of reliability reporting, analyses would be based on summaries from the data partner. Comparing or combining data across multiple data partners would require an effort to standardize or normalize the data to obtain equivalency of input data. To meet the goal of data from 10% of the installed wind capacity by 2012, the sheer magnitude of data may necessitate use of some form of summarized data. In most cases, this summary information can be determined by assessing SCADA and work order data.

To conduct reliability analysis using summarized data, the following information is needed for each type of downtime or maintenance:

- Event Code: Unique identifier for event type
- Event Name: Descriptive label for event type
- Event Rate (single value and/or distribution)
- Downtime Duration (single value and/or distribution)
- Event Type: Type of downtime, e.g., failure, preventative maintenance
- Event Cost: Cost per occurrence and/or hour of downtime

Data Challenges

Failure data for plant equipment and processes likely contains issues with the definition of “failure,” data accuracy, data recording ambiguities, data accessibility, and incomplete cost information. It is difficult to identify a base set of “downtimes” for the turbine when SCADA and work order data do not match. When a downtime period is determined, it may be difficult to identify the cause for that downtime. While SCADA codes are faithfully recorded, the actual component that caused the event is often not identified explicitly. Work orders give insight into the failure cause and repairs performed, but they are not generated each time the turbine goes down. Often, work orders list the amount of time it took for the operator to fix the turbine, not the actual time the turbine was down.

Costs for parts replacement, repair, and maintenance activities are useful for assessing expenses and can help determine inventory spares, and total system impacts.

Data Formatting and Normalization

Wind plants have many different methods for gathering and processing their data. Although turbine manufacturers collect similar data values, the data points are structured, stored, named, and aggregated in a variety of ways. An understanding of these differences and a standardized approach for inputs into the database are necessary. To get data into the National Reliability Database, the proper structure must be in place to import the data. For SCADA data, this is usually a fairly straightforward process, as data can be put into comma separated value (CSV) format or exported to an Excel spreadsheet.

As part of data entry for the database, SCADA event codes are matched to a generic physical breakdown of wind turbine components. A wind turbine taxonomy has been developed by the Wind Plant Reliability Database and Analysis Program (see Appendix A for the taxonomy breakdown) that lists the components and subcomponents of most modern wind turbines. SCADA codes from the data partners’ plant SCADA systems are each matched to a single component in this taxonomy. For example, a SCADA code by the name of “Generator Overspeed Sensor” would be matched to the

“Generator::Shaft::Encoder” component in the taxonomy. Once the data has been entered and matched to the appropriate component, analysis can begin.

Work order data is also entered into the National Reliability Database. The process entails preparing electronic work order data into the proper format so that the information matches the fields in the database tables. Paper work orders must be transferred by manually inputting the information into the database table. This is a time consuming process, but the information in the work orders is valuable as a useful work order will contain information regarding symptom, cause and corrective action.

Analysis Process

Once data is gathered from a data partner, normalized, and entered into the National Reliability Database, it is ready for analysis. First, individualized reporting and analysis is performed for each data partner. Then, the set of data from all partners is analyzed collectively to develop a national baseline for the industry, which is used to produce national-level reporting and analysis.

The software used to perform the analysis is a powerful Sandia-developed reliability analysis tool called Pro-Opta. Pro-Opta has been used in many technologies and operations ranging from fleets of mobile units to logistically complex operational installations to productions facilities (see Appendix C for more information on Pro-Opta).

Features of Pro-Opta include:

- Analysis of system performance (availability, mean time between failure, downtime, reliability, and cost), based on field failure and maintenance data. Reporting includes analysis of overall plant, individual turbines, and weak-link analysis of individual failure modes' contributions to performance.

- An optimization to identify the best reliability and O&M improvements, given a variety of what-if scenarios/trade-offs and user-defined goals/objectives (e.g., minimize Annual Cost and Weight, while simultaneously maximizing Availability).

- An optimization to identify the ideal spare parts inventory, given user-defined goals/objectives (e.g., maximize Availability, while simultaneously minimizing the Inventory's total volume). Both optimizations can simultaneously model multiple designs/plants, including those that share some, but not all, failure modes and/or inventory items.

- Consolidation of field failure and maintenance data into a fault tree model of the system (including O&M costs, calculation of uncertainties and probability distributions, and estimates of correlation between failure modes).

Reporting and Analysis Output

Reporting and analysis is performed on two levels – national baseline reports and partner reports. National Baseline Reports illustrate the national performance of the wind energy industry as a whole. These reports document performance, highlight unexpected (both positive and negative) findings, and make TIO (Technology Improvement Opportunity) recommendations. Partner Reports are provided to each of our data partners illustrating their wind plant(s) performance and comparing this to the national baseline. In addition to the partner report, custom analysis may be performed for partners with specific questions, as time and resources permit.

Partner Report - Sample

Partner reports contain graphs, charts, and analysis results intended to address two distinct needs: understanding of the individual plant's performance, and comparing an individual plant against the national baseline. Depending on the structure of the NDA with the partner, this may also include comparing a single plant against other plants owned by the same entity. The following paragraphs and figures illustrate a sample of the type of reporting that will be created for partners. (See Appendix B for a complete sample report.) Also included in the sample report are definitions for the reliability terms listed in the figures. Due to the proprietary nature of the data and the program, actual results cannot be shown for a partner data; thus, these charts and values are not based on actually data, but are intended for illustration purposes. National statistics are not yet ready for publication, but reliability models will be delivered in FY09.

The report begins with high-level "Summary Statistics" of the plant's performance, which is contrasted with National performance, as shown in Table 1: Summary Statistics – Plant vs. National below. This information creates a one-page "Executive" summary of the plant's performance. In addition to this summary for all maintenance and downtime events at the plant, the Failures, Faults, and Scheduled Maintenance are called out separately.

Summary Statistics

		Last 6 Months (1/1-6/30/08)		*All Available Data*	
Events Included	**Metric**	**Plant Mean Value**	**National Mean Value**	**Plant Mean Value**	**National Mean Value**
All Events	**Operational Availability**	X%	X%	X%	X%
	Wind Utilization	X%	X%	X%	X%
	Utilization	X%	X%	X%	X%
	MTBE (operating hrs)	X	X	X	X
	Mean Downtime (hrs)	X	X	X	X
	Annual Cost (per Turbine)	$X	$X	$X	$X
Failures	**Intrinsic Availability**	X%	X%	X%	X%
	MTBF (operating hrs)	X	X	X	X
	Mean Failure Downtime (hrs)	X	X	X	X
	Annual Failure Cost (per Turbine)	$X	$X	$X	$X
Faults	**MTB Fault** (operating hrs)	X	X	X	X
	Mean Fault Downtime (hrs)	X	X	X	X
	Annual Fault Cost (per Turbine)	$X	$X	$X	$X
Scheduled Maintenance	**MTB Scheduled Maintenance** (operating hrs)	X	X	X	X
	Mean Scheduled Downtime (hrs)	X	X	X	X
	Annual Scheduled Cost (per Turbine)	$X	$X	$X	$X

All metrics, including annual cost, are for a single, representative, turbine

Table 1: Summary Statistics – Plant vs. National

Another key summary element of the report is the “Time Allocation” chart, which illustrates how a typical turbine spends an average month. Time is broken out based on Generation and Wind, with subcategories where appropriate, as illustrated below in Figure 1: Turbine Time Allocation Pie Chart. This allows for multiple definitions of availability and utilization to be explored from within a single graph.

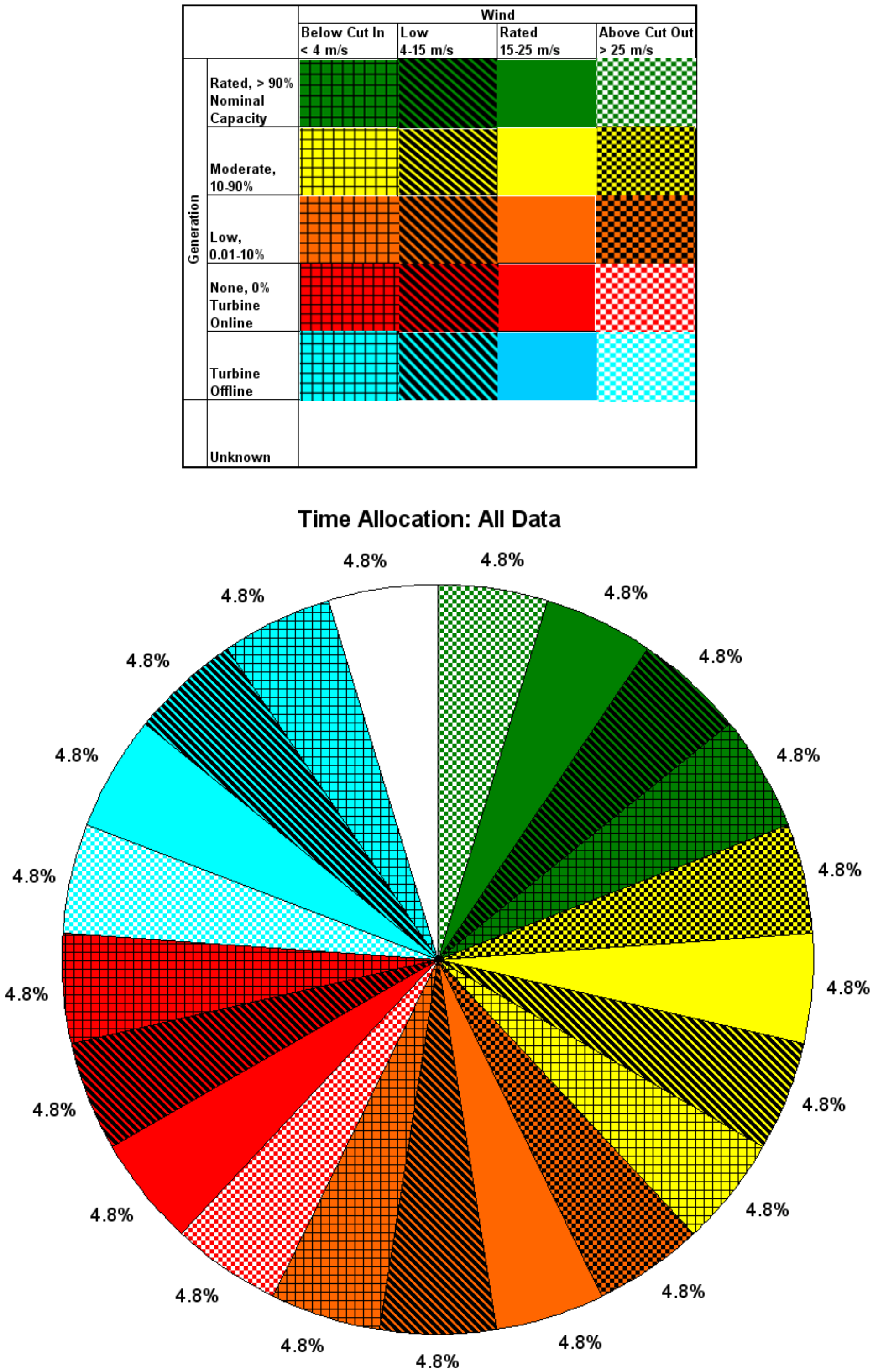


Figure1: Turbine Time Allocation Pie Chart

The report also provides trending information for both the plant and the National baseline including Availability, Utilization, Mean Downtime, Mean Time Between Events, Cost, and Event Counts. An example Availability/Utilization trend graph is shown below in Figure 2: Availability and Utilization Trends.

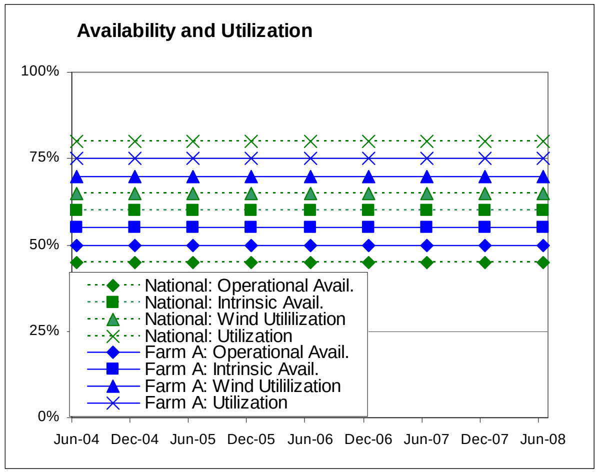


Figure 2: Availability and Utilization Trends

In addition to information about the performance of the plant as a whole, various wind turbine components are analyzed and Pareto charts are created to show both their contributions to overall performance and overall turbine-to-turbine variability. These Pareto charts are created for Availability, Event Frequency, Downtime, and Cost. The value of these charts is to show what events have the greatest effect on turbine performance. This knowledge creates an understanding of areas of reduced reliability performance at the component level and can help operators prioritize how they approach maintenance, develop spares strategies, and implement technologies such as condition based maintenance (CBM) that can help proactively decrease failure rates. See Figure 3: Cost Performance Drivers. Additionally, variability drivers are events which affect the uncertainty in reliability metrics. This is illustrated in Figure 4: Cost High Variability Drivers, with the most significant negative effect on the certainty of the metric listed. Larger variability implies bigger differences from turbine to turbine and more risk when planning for reliability impacts.

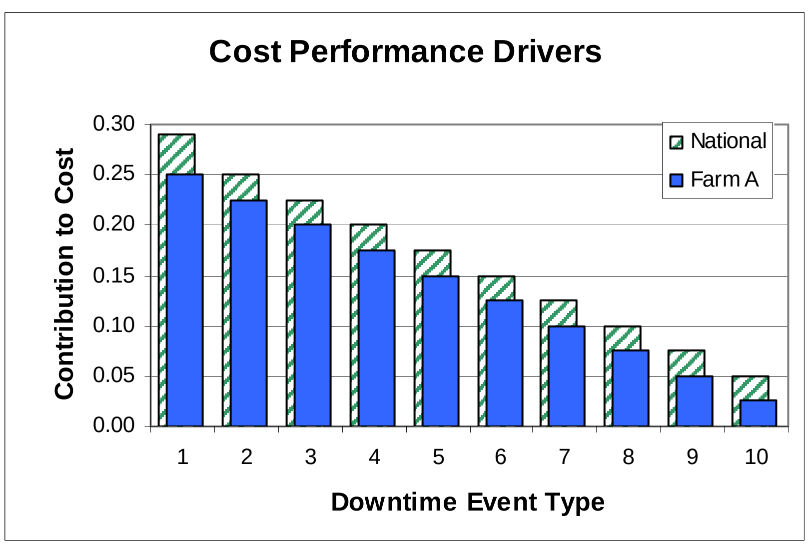


Figure 3: Cost Performance Drivers

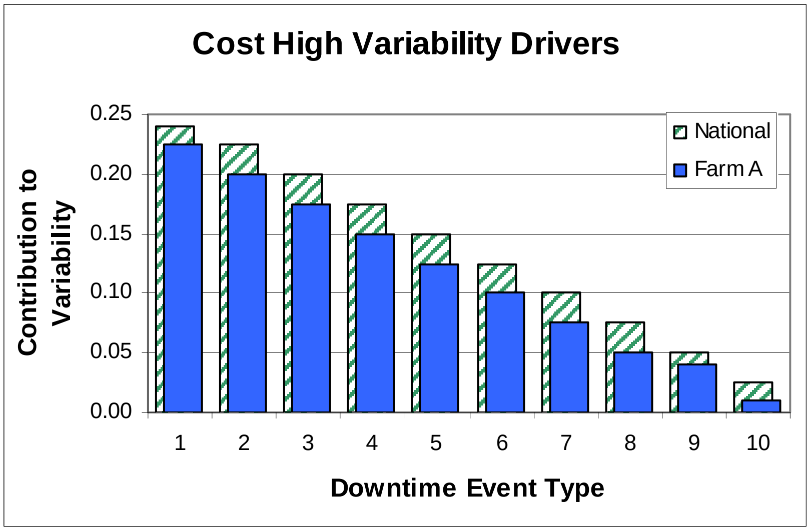


Figure 4: Cost High Variability Drivers

Along with exploring the performance of the various components, individual performance for each turbine is also calculated. This information allows for comparison across turbines or sections of a plant, and allows for "weak links" to be quickly detected. See Table 2: Turbine Summary Statistics, below, for an example.

Turbine	Operational Availability	Mean Time Between Events (hours)	Average Cost Per Event	Mean Downtime Per Event (hours)
Turbine 0001	X%	X	$X	X
Turbine 0002	X%	X	$X	X
Turbine 0003	X%	X	$X	X
Turbine 0004	X%	X	$X	X
Turbine 0005	X%	X	$X	X
Turbine 0006	X%	X	$X	X
Turbine 0007	X%	X	$X	X
Turbine 0008	X%	X	$X	X
Turbine 0009	X%	X	$X	X
Turbine 0010	X%	X	$X	X
…	…	…	…	…

Table 2: Turbine Summary Statistics

Appendix A: Taxonomy

The following taxonomy has been developed for the Wind Plant Reliability Database and Analysis Program. All data will be associated with one of the components listed.

Blade

- Blade::Aero-dynamic brake
- Blade::Internal structure - laminates
- Blade::Lightning protection
- Blade::Paint and coatings
- Blade::Skins - laminates
- Blade::T-bolt/root insert
- Blade::De-icing system

Rotor

- Rotor::Nose cone
- Rotor::Pitch system
  - Rotor::Pitch system::Linear hydraulic drive
    - Rotor::Pitch system::Linear hydraulic drive::Accumulator
    - Rotor::Pitch system::Linear hydraulic drive::Pump
    - Rotor::Pitch system::Linear hydraulic drive::Pump motor
    - Rotor::Pitch system::Linear hydraulic drive::Proportional valve
    - Rotor::Pitch system::Linear hydraulic drive::Miscellaneous hydraulic
    - Rotor::Pitch system::Linear hydraulic drive::Position sensor
    - Rotor::Pitch system::Linear hydraulic drive::Hose/fitting
    - Rotor::Pitch system::Linear hydraulic drive::Spherical bushing
    - Rotor::Pitch system::Linear hydraulic drive::Cylinder
    - Rotor::Pitch system::Linear hydraulic drive::Bushing
    - Rotor::Pitch system::Linear hydraulic drive::Linkage
    - Rotor::Pitch system::Linear hydraulic drive::Position controller
    - Rotor::Pitch system::Linear hydraulic drive::Limit switch
  - Rotor::Pitch system::Rotary electric drive
    - Rotor::Pitch system::Rotary electric drive::Motor
    - Rotor::Pitch system::Rotary electric drive::Gear reducer
    - Rotor::Pitch system::Rotary electric drive::Pinion
    - Rotor::Pitch system::Rotary electric drive::Motor cooling fan
    - Rotor::Pitch system::Rotary electric drive::Motor brake
    - Rotor::Pitch system::Rotary electric drive::Power electronics/drive
    - Rotor::Pitch system::Rotary electric drive::Cabling
    - Rotor::Pitch system::Rotary electric drive::Contactor/circuit breaker.fuse
    - Rotor::Pitch system::Rotary electric drive::Battery
    - Rotor::Pitch system::Rotary electric drive::Battery charger
    - Rotor::Pitch system::Rotary electric drive::Encoder
    - Rotor::Pitch system::Rotary electric drive::Limit switch
    - Rotor::Pitch system::Rotary electric drive::Power supply
    - Rotor::Pitch system::Rotary electric drive::Heater

      - Rotor::Pitch system::Rotary electric drive::Miscellaneous electrical
    - Rotor::Pitch system::Mechanical drive
      - Rotor::Pitch system::Mechanical drive::Bearings
      - Rotor::Pitch system::Mechanical drive::Gears
      - Rotor::Pitch system::Mechanical drive::Motor
      - Rotor::Pitch system::Mechanical drive::Pitch cylinder linkage
    - Rotor::Pitch system::Pitch gear
    - Rotor::Pitch system::Bearing
      - Rotor::Pitch system::Bearing::Seal
      - Rotor::Pitch system::Bearing::Auto-lube system
  - Rotor::Hub
  - Rotor::Slip ring assembly
  - Rotor::Root attachment
    - Rotor::Root attachment::Bolts

Drivetrain

  - Drivetrain::Low speed shaft
    - Drivetrain::Low speed shaft::Main bearing
    - Drivetrain::Low speed shaft::Main shaft
    - Drivetrain::Low speed shaft::Main bearing seal
    - Drivetrain::Low speed shaft::Compression coupling
    - Drivetrain::Low speed shaft::Rotor lock
  - Drivetrain::High speed shaft
    - Drivetrain::High speed shaft::High speed coupling
    - Drivetrain::High speed shaft::Transmission shaft
  - Drivetrain::Braking system
    - Drivetrain::Braking system::Brake disc
    - Drivetrain::Braking system::Brake calipers
    - Drivetrain::Braking system::Brake pads
    - Drivetrain::Braking system::Transmission lock

Gearbox

  - Gearbox::Bearings
    - Gearbox::Bearing::Planet bearing
    - Gearbox::Bearing::Carrier bearing
    - Gearbox::Bearing::Shaft bearing
  - Gearbox::Gears
    - Gearbox::Gears::Planet gear
    - Gearbox::Gears::Ring gear
    - Gearbox::Gears::Sun gear
    - Gearbox::Gears::Spur gear
    - Gearbox::Gears::Hollow shaft
  - Gearbox::Lube system
    - Gearbox::Lube system::Cooling system
      - Gearbox::Lube system::Cooling system::Coolant pump
      - Gearbox::Lube system::Cooling system::Radiator
    - Gearbox::Lube system::Primary filtration

Gearbox::Lube system::Secondary filtration
Gearbox::Lube system::Lube pump
Gearbox::Lube system::Lube pump motor
Gearbox::Lube system::Hose/fitting
Gearbox::Lube system::Reservoir
Gearbox::Lube system::Sensor
Gearbox::Housing
Gearbox::Torque arm system
Gearbox::Torque arm system::Bushing

Generator

Generator::Cooling system
Generator::Cooling system::Filter
Generator::Cooling system::Cooling fan
Generator::Cooling system::Pump
Generator::Cooling system::Pump motor
Generator::Cooling system::Reservoir
Generator::Cooling system::Radiator
Generator::Cooling system::Hose/fitting
Generator::Stator
Generator::Stator::Winding
Generator::Stator::Lamination
Generator::Rotor
Generator::Rotor::Winding
Generator::Rotor::Lamination
Generator::Rotor::Encoder
Generator::Rotor::Shaft
Generator::Controller::Exciter
Generator::Controller::Resistance controller
Generator::Controller::Slip ring
Generator::Controller::Brush
Generator::Housing
Generator::Commutator and brushes
Generator::Bearings
Generator::Bearings::Auto-lube system

Electrical

Electrical::Power converter
Electrical::Power converter::IGBT module
Electrical::Power converter::Rectifier bridge
Electrical::Power converter::Crowbar system
Electrical::Power converter::Driver/control board
Electrical::Power converter::Harmonics filter
Electrical::PFC system
Electrical::PFC system::Capacitors
Electrical::PFC system::Harmonics filter
Electrical::PFC system::Contactor

Electrical::Soft starter
Electrical::Wiring and connections
Electrical::Grounding system
Electrical::Main transformer
Electrical::Main transformer::Pad mounted transformer
Electrical::Main transformer::Nacelle-mounted transformer
Electrical::Components
Electrical::Components: Main contactor
Electrical::Components: Main circuit breaker
Electrical::Components: Main disconnect
Electrical::Components: Motor contactor
Electrical::Components: Power supply
Electrical::Components: Fuse
Electrical::Components: Relay
Electrical::Components: Cabinet heater
Electrical::Components: Miscellaneous

Nacelle

Nacelle::Enclosure
Nacelle::Meteorological equipment
Nacelle::Meteorological equipment::Anemometer
Nacelle::Meteorological equipment::Anemometer::De-icing heater
Nacelle::Meteorological equipment::Wind vane
Nacelle::Meteorological equipment::Temperature sensor
Nacelle::FAA lights
Nacelle::Internal environment
Nacelle::Internal environment::Nacelle heater
Nacelle::Internal environment::Nacelle vent
Nacelle::Internal environment::Nacelle lighting
Nacelle::Crane

Yaw

Yaw::Cable twist/untwist
Yaw::Brake
Yaw::Hydraulics::Accumulator
Yaw::Hydraulics::Pump
Yaw::Hydraulics::Hoses and valves
Yaw::Hydraulics::Motor
Yaw::Drives
Yaw::Drives::Motor
Yaw::Drives::Gear reducer
Yaw::Drives::Pinion
Yaw::Bearings (slew ring)
Yaw::Gear
Yaw::Gear::Lubrication system
Yaw::Damper
Yaw::Hydraulics

Control system

- Control system::Sensors
    - Control system::Sensors::Static::Generator temp
    - Control system::Sensors::Static::Particulate sensor
    - Control system::Sensors::Static::Power metering
    - Control system::Sensors::Static::Yaw position proximity
    - Control system::Sensors::Static::Gearbox temp
    - Control system::Sensors::Dynamic::Vibration sensors
- Control system::Communications
- Control system::SCADA interface
- Control system::Controller
    - Control system::Controller::Software
    - Control system::Controller::Central processor
    - Control system::Controller::I/O board
    - Control system::Controller::Power supply
    - Control system::Controller::User interface
- Control system::Cabinet
- Control system::UPS
    - Control system::UPS::Battery

Foundation and tower

- Foundation and tower::Foundation
    - Foundation and tower::Foundation::Bolts
- Foundation and tower::Tower structure
    - Foundation and tower::Tower structure::Paint and coatings
    - Foundation and tower::Tower structure::Bolts
- Foundation and tower::Tower equipment
    - Foundation and tower::Tower equipment::Climb assist
    - Foundation and tower::Tower equipment::Ladder/hatches/internals

Balance of plant

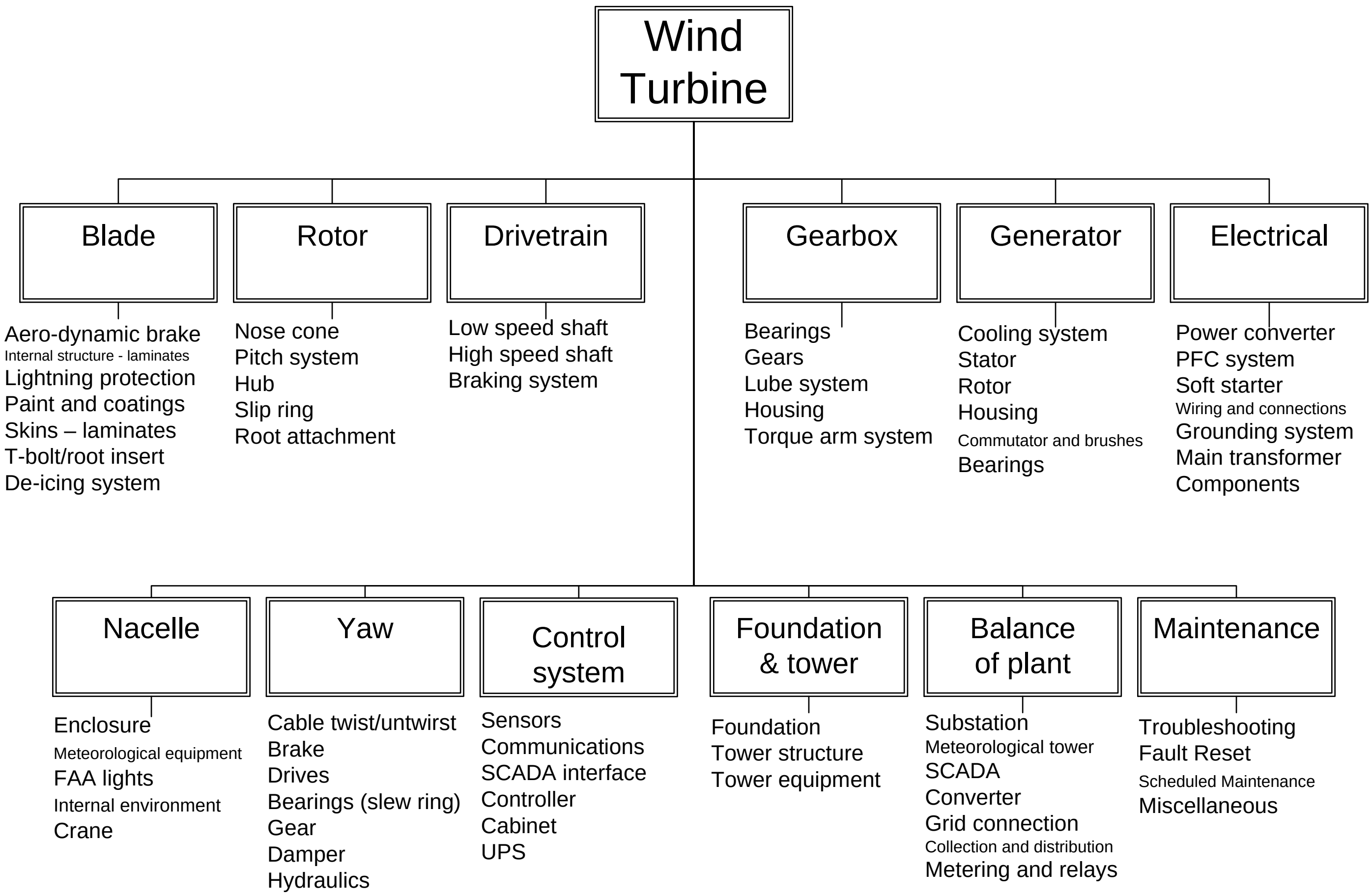
- Balance of Plant::Substation
    - Balance of Plant::Substation::VAR Control system (Reactive Power control)
    - Balance of Plant::Substation::Potential transformers
    - Balance of Plant::Substation::Breakers
    - Balance of Plant::Substation::Current transformers
    - Balance of Plant::Substation::Lightning arrestors
    - Balance of Plant::Substation::Switching
    - Balance of Plant::Substation::Power transformers (Volt adj.; load tap chngrs)
        - Balance of Plant::Substation::Power transformers::Power compensation
- Balance of Plant::Met tower
    - Balance of Plant::Meteorological tower::Anemometer
    - Balance of Plant::Meteorological tower::Wind vane
    - Balance of Plant::Meteorological tower::Barometer
- Balance of Plant::SCADA
    - Balance of Plant::SCADA::Server
    - Balance of Plant::SCADA::Communications switch

Balance of Plant::SCADA::Cabling
Balance of Plant::SCADA::Cooling
Balance of Plant::SCADA::Software
Balance of Plant::Converter
Balance of Plant::Grid connection
Balance of Plant::Grid connection::Utility communication
Balance of Plant::Collection and distribution
Balance of Plant::Metering and relays

Maintenance

Maintenance::Troubleshooting
Maintenance::Fault reset
Maintenance::Scheduled maintenance
Maintenance::Scheduled maintenance::3-month-int
Maintenance::Scheduled maintenance::6-month-int
Maintenance::Scheduled maintenance::12-month-int
Maintenance::Miscellaneous
Maintenance::Miscellaneous::Punch list
Maintenance::Miscallaneous::QC punch list
Maintenance::Miscellaneous::Emergency stop

Taxonomy (Top 2 levels)



Appendix B: Report Template for individualized reports to Partners

National Wind Energy Reliability Database

Wind Plant Data Partner Report
COMPANY: Company X
PLANT: Plant A

Report Date: 6/30/2008

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Table of Tables

Summary Statistics

		Last 6 Months (1/1-6/30/08)		*All Available Data*	
Events Included	**Metric**	**Plant Mean Value**	**National Mean Value**	**Plant Mean Value**	**National Mean Value**
All Events	**Operational Availability**	X%	X%	X%	X%
	Wind Utilization	X%	X%	X%	X%
	Utilization	X%	X%	X%	X%
	MTBE (operating hrs)	X	X	X	X
	Mean Downtime (hrs)	X	X	X	X
	Annual Cost (per Turbine)	$X	$X	$X	$X
Failures	**Intrinsic Availability**	X%	X%	X%	X%
	MTBF (operating hrs)	X	X	X	X
	Mean Failure Downtime (hrs)	X	X	X	X
	Annual Failure Cost (per Turbine)	$X	$X	$X	$X
Faults	**MTB Fault** (operating hrs)	X	X	X	X
	Mean Fault Downtime (hrs)	X	X	X	X
	Annual Fault Cost (per Turbine)	$X	$X	$X	$X
Scheduled Maintenance	**MTB Scheduled Maintenance** (operating hrs)	X	X	X	X
	Mean Scheduled Downtime (hrs)	X	X	X	X
	Annual Scheduled Cost (per Turbine)	$X	$X	$X	$X

All metrics, including annual cost, are for a single, representative, turbine

Table B-1: Summary Statistics – Plant vs. National

Definitions & Terms

- **Annual Cost**: the expected yearly cost for a single turbine, due to all events
  - **Annual Failure Cost**: the expected yearly cost for a single turbine, due to failures
  - **Annual Fault Cost**: the expected yearly cost for a single turbine, due to faults
  - **Annual Scheduled Cost**: the expected yearly cost for a single turbine, due to scheduled maintenance
- **Availability**: the percent of time a system is ready for use (Note: Availability can have many different definitions and formulas.)
  - **Operational Availability**: the percent of total calendar time that the system is either generating or is ready to generate (i.e., the percent of total calendar time that the system is NOT down for events)

    $$= (GeneratingHours + OtherUpTime) / CalendarHours$$

  - **Intrinsic Availability**: the percent of operating and downtime that the system is operating; the percent of time the system is functioning, taking into account only the operating time and unscheduled downtime

    $$= MeanTimeBetweenFailureFault / (MeanTimeBetweenFailureFault + MeanFailureFaultDowntime)$$

    $$= GeneratingHours / (GeneratingHours + DowntimeDueToFailiuresAndFaults)$$

- **Calendar Hours**: for a given analysis period, the total number of hours
- **Event**: scheduled or unscheduled occurrence that stops the turbine or takes it out of service
- **Event Frequency**: the expected number of events per generating hour = 1/MTBE
- **Failure**: an unplanned event that must be reset or fixed at the turbine
- **Fault**: an unplanned event that can be reset automatically or remotely
- **Generating**: the turbine average output is > 0 kW during the measurement period (typically 10 minutes or 1 hour)

Generation	**Definition**
None	0% of Rated Capacity
Low	0.01 – 10% of Rated Capacity
Moderate	10 – 90% of Rated Capacity
Rated	> 90% of Rated Capacity

- **Generating Hours**: for a given analysis period, the time the system is Generating
- **Mean Downtime**: the average duration of an event (in hours)
  - **Mean Failure Downtime**: the average duration of an event that is a failure
  - **Mean Fault Downtime**: the average duration of an event that is a fault
  - **Mean Failure/Fault Downtime**: the average duration of an event that is either a failure or fault
  - **Mean Scheduled Downtime**: the average duration of an event that is a scheduled maintenance event

- **MTBE**: Mean Time Between Events: the average number of generating hours between events
  - **MTBF**: Mean Time Between Failures: the average number of generating hours between events that are failures
  - **MTB Fault**: Mean Time Between Faults: the average number of generating hours between events that are faults
  - **Mean Time Between Failure/Fault**: the average number of generating hours between events that are either failures or faults
  - **MTB Scheduled Maintenance**: Mean Time Between Scheduled Maintenance: the average number of generating hours between events that are scheduled maintenance events
- **Other Up Time**: for a given analysis period, the time the system is ready to generate, but not actively generating (i.e., it is idle); the system is neither actively producing nor down for an event
- **Scheduled Maintenance**: a planned event
- **Unavailability**: 1 – Availability
- **Utilization**: for a given analysis period, the percent of Calendar Hours that the system was Generating

  $= GeneratingHours / CalendarHours$
- **Wind Hours**: for a given analysis period, the total number of hours that the anemometer registered a mean wind speed of 4 – 25 m/s.

Wind	**Definition**
Below Cut In	0 – 4 m/s
Low	4 – 15 m/s
Rated	15 – 25 m/s
Above Cut Out	> 25 m/s

- **Wind Utilization**: for a given analysis period, the percent of Wind Hours that the system was Generating

  $= GeneratingHours / WindHours$

Average Time Allocation

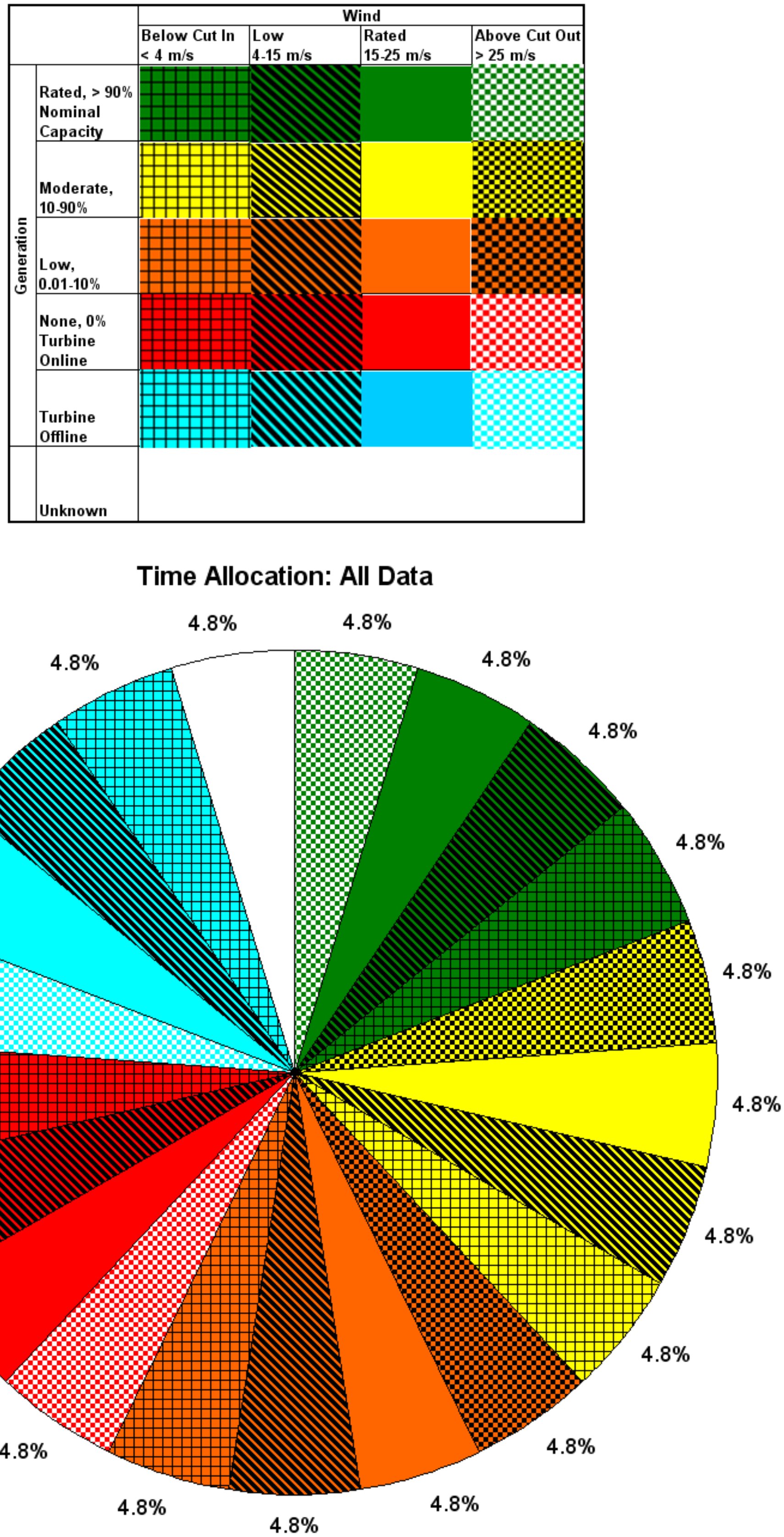


Figure B-1: Turbine Time Allocation Pie Chart

Parts Replacement Summary

This summary illustrates the frequency ("Failure Rate") and duration ("Mean Downtime") for failures that lead to parts replacement. Scheduled maintenance, faults, and failures that do not require parts replacement are not included. Failure Rate is the expected number of failures (requiring parts replacement) per calendar year for one turbine. Mean Downtime is the expected number of hours of downtime for each event.

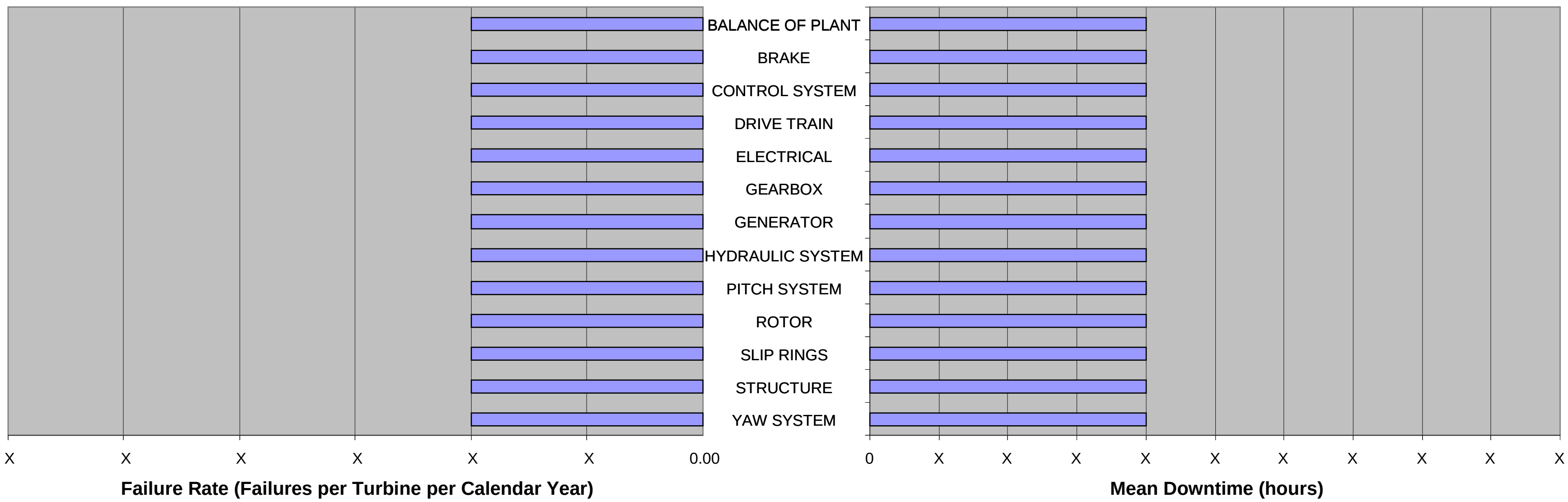


Figure B-2: Major Parts Replacements – All Data

Trends

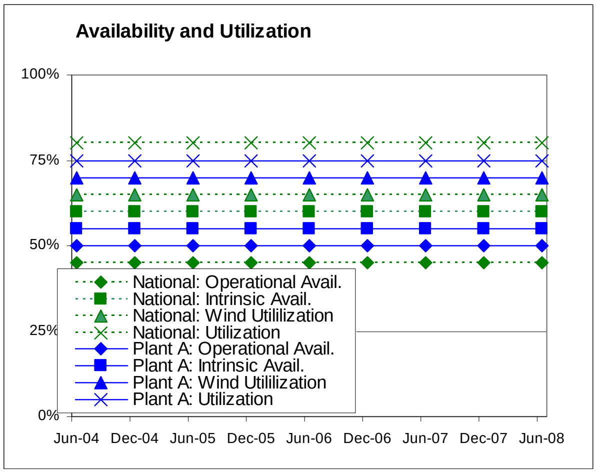


Figure B-3: Availability and Utilization Trends

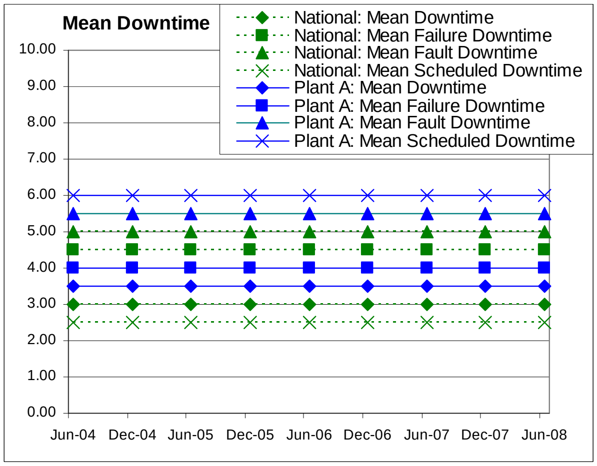


Figure B-4: Mean Downtime Trends

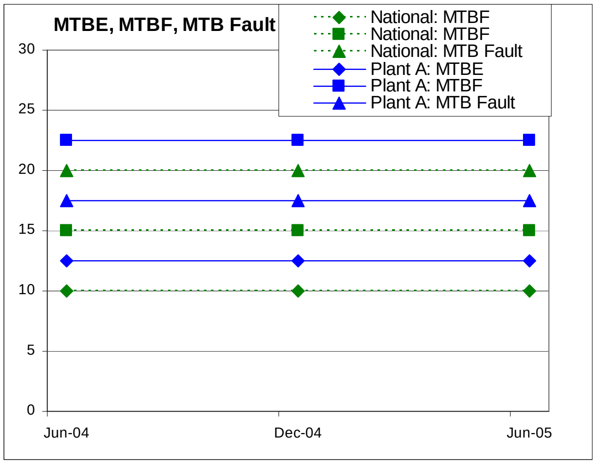


Figure B-5: MTBE, MTBF, MTB Fault Trends

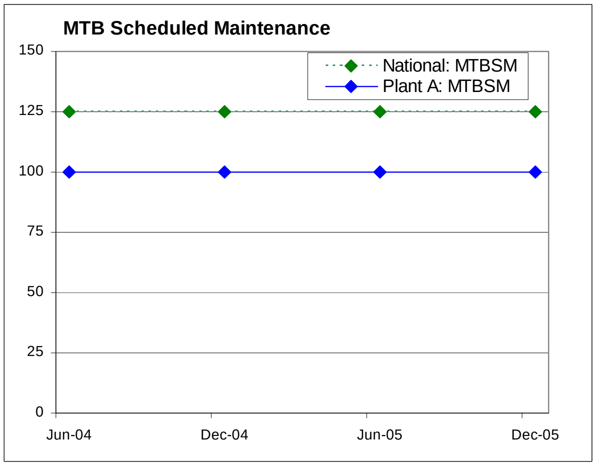


Figure B-6: MTB Scheduled Maintenance Trends

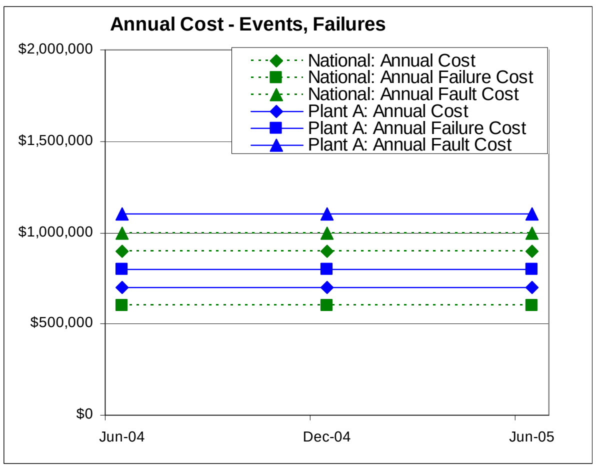


Figure B-7: Annual Event and Failure Cost Trends

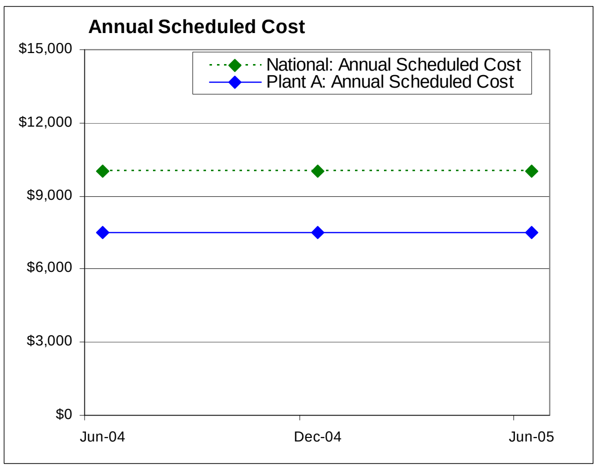


Figure B-8: Annual Scheduled Cost Trends

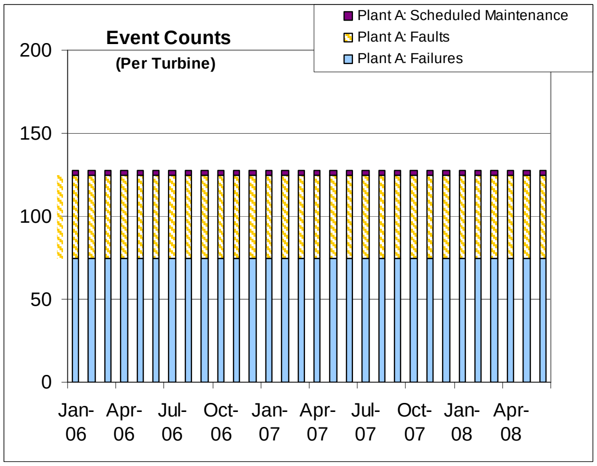


Figure B-9: Plant Event Count Trends

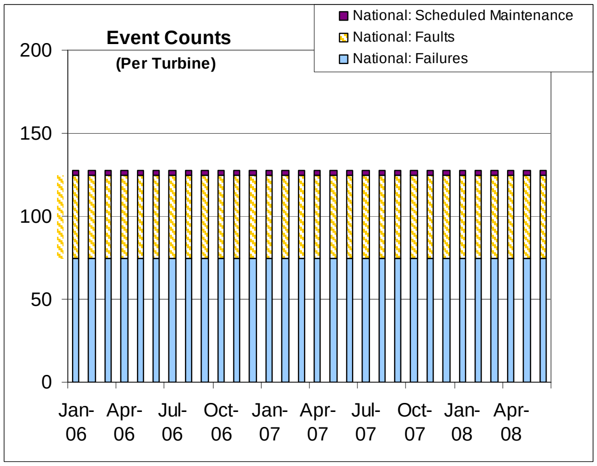


Figure B-10: National Event Count Trends

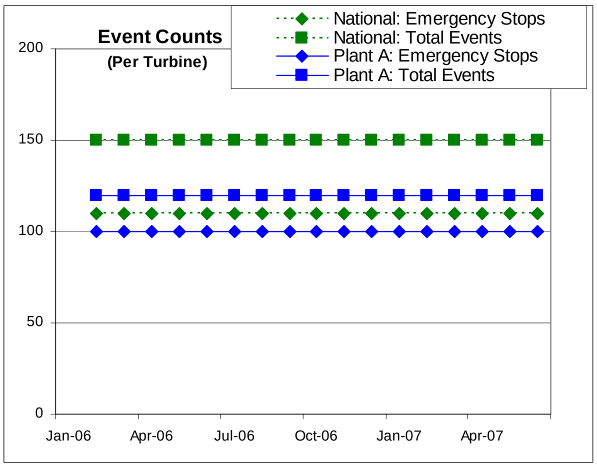
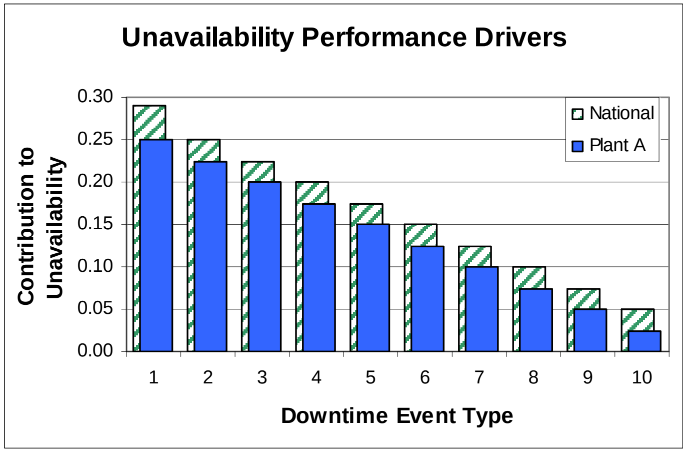


Figure B-11: Event and Emergency Count Trends

Performance Drivers – Roll Up

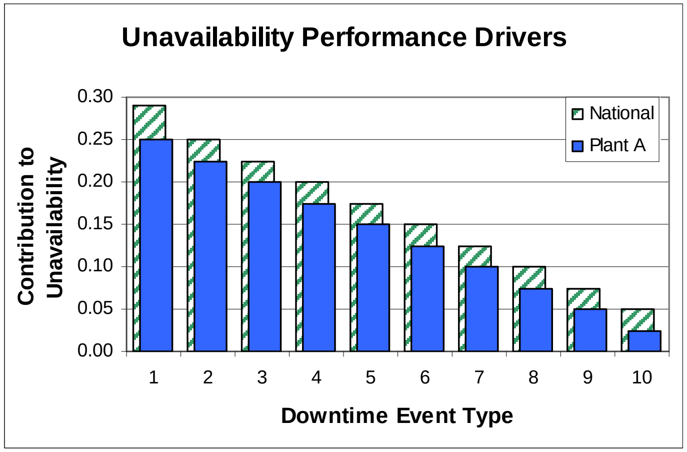
Performance drivers are events which affect reliability metrics. The following figures illustrate the performance drivers (rolled up to the second level of detail in the taxonomy[1]) with the most significant negative effect on the metric listed. **For all these graphs, bigger = worse.** The top performance drivers for the plant are illustrated, along with the National value for these drivers.

Operational Unavailability Performance Drivers – Rollup



Downtime Event Type	
1	Component A
2	Component B
3	Component C
4	Component D
5	Component E
6	Component F
7	Component G
8	Component H
9	Component I
10	Component J

Figure B-12: Operational Unavailability Performance Drivers – Rollup, All Data

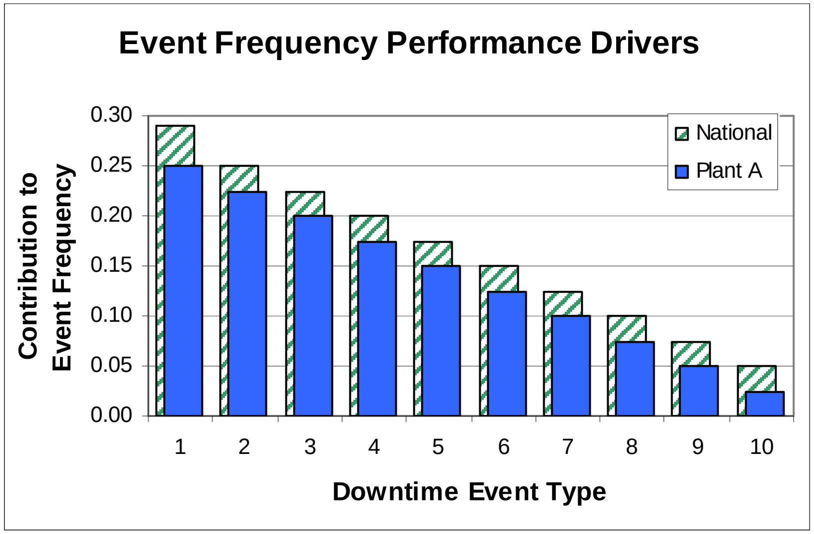


Downtime Event Type	
1	Component A
2	Component B
3	Component C
4	Component D
5	Component E
6	Component F
7	Component G
8	Component H
9	Component I
10	Component J

Figure B-13: Operational Unavailability Performance Drivers – Rollup, 1/1-6/30/2008

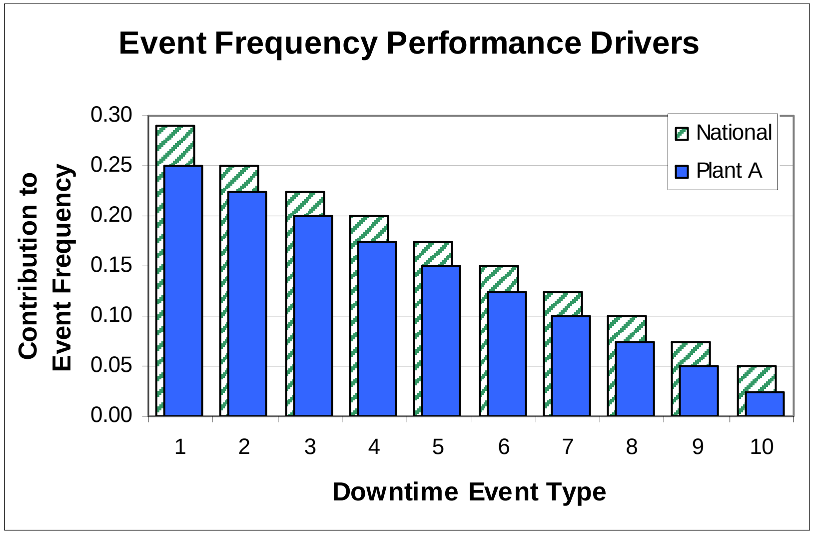
[1] See User's Guide for illustration of taxonomy.

Event Frequency (MTBE) Performance Drivers – Rollup



Downtime Event Type	
1	Component A
2	Component B
3	Component C
4	Component D
5	Component E
6	Component F
7	Component G
8	Component H
9	Component I
10	Component J

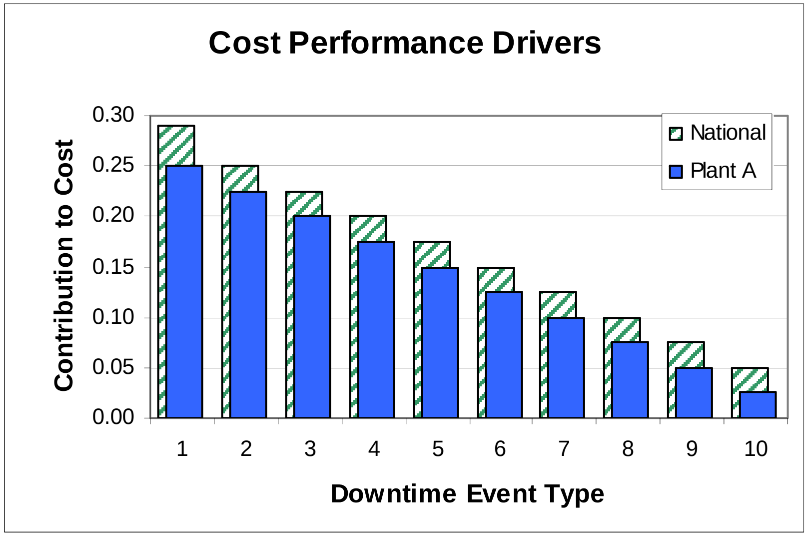
Figure B-14: Event Frequency Performance Drivers – Rollup, All Data



Downtime Event Type	
1	Component A
2	Component B
3	Component C
4	Component D
5	Component E
6	Component F
7	Component G
8	Component H
9	Component I
10	Component J

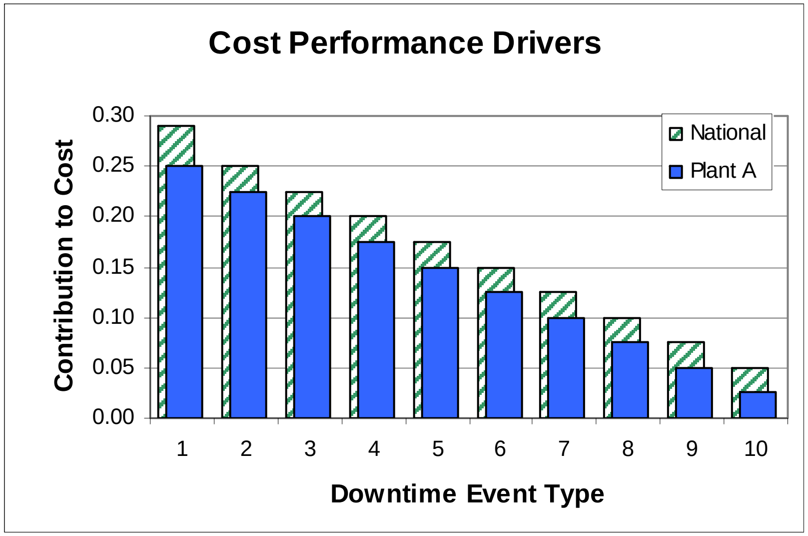
Figure B-15: Event Frequency Performance Drivers – Rollup, 1/1-6/30/2008

Cost Performance Drivers – Rollup



Downtime Event Type	
1	Component A
2	Component B
3	Component C
4	Component D
5	Component E
6	Component F
7	Component G
8	Component H
9	Component I
10	Component J

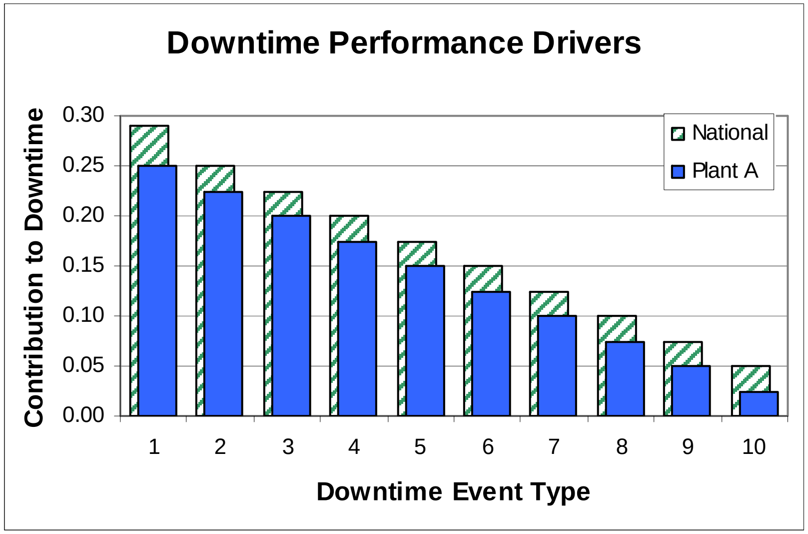
Figure B-16: Cost Performance Drivers – Rollup, All Data



Downtime Event Type	
1	Component A
2	Component B
3	Component C
4	Component D
5	Component E
6	Component F
7	Component G
8	Component H
9	Component I
10	Component J

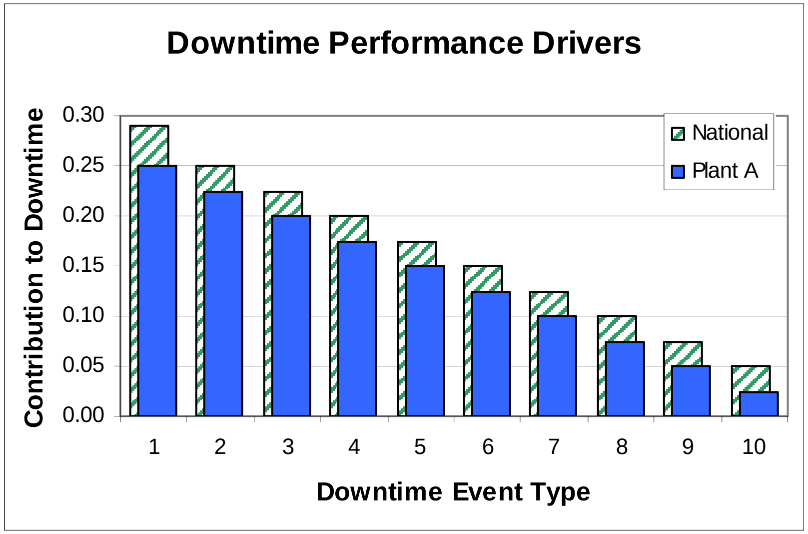
Figure B-17: Cost Performance Drivers – Rollup, 1/1-6/30/2008

Downtime Performance Drivers – Rollup



Downtime Event Type	
1	Component A
2	Component B
3	Component C
4	Component D
5	Component E
6	Component F
7	Component G
8	Component H
9	Component I
10	Component J

Figure B-18: Downtime Performance Drivers – Rollup, All Data



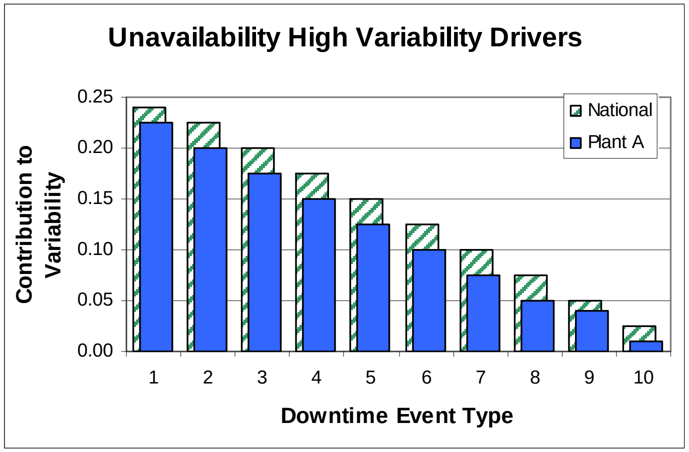
Downtime Event Type	
1	Component A
2	Component B
3	Component C
4	Component D
5	Component E
6	Component F
7	Component G
8	Component H
9	Component I
10	Component J

Figure B-19: Downtime Performance Drivers – Rollup, 1/1-6/30/2008

High Variability Drivers – Roll Up

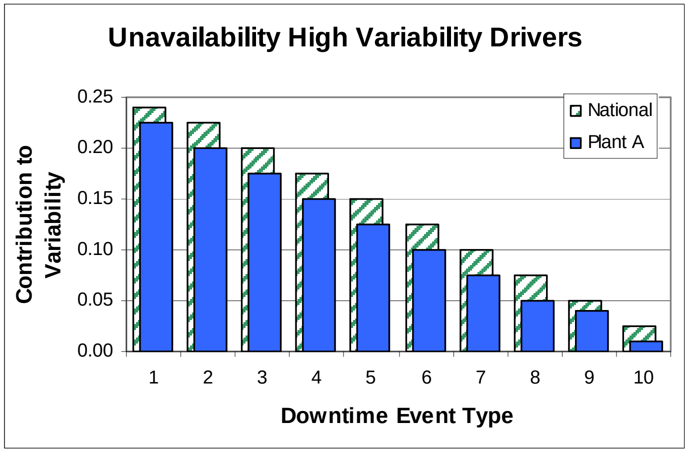
Variability drivers are events which affect the uncertainty in reliability metrics. The following figures illustrate the variability drivers (rolled up to the second level of detail in the taxonomy) with the most significant negative effect on the certainty of the metric listed. Larger variability implies bigger differences from turbine to turbine and more risk when planning for reliability impacts.

Operational Unavailability High Variability Drivers – Rollup



	Downtime Event Type
1	Component A
2	Component B
3	Component C
4	Component D
5	Component E
6	Component F
7	Component G
8	Component H
9	Component I
10	Component J

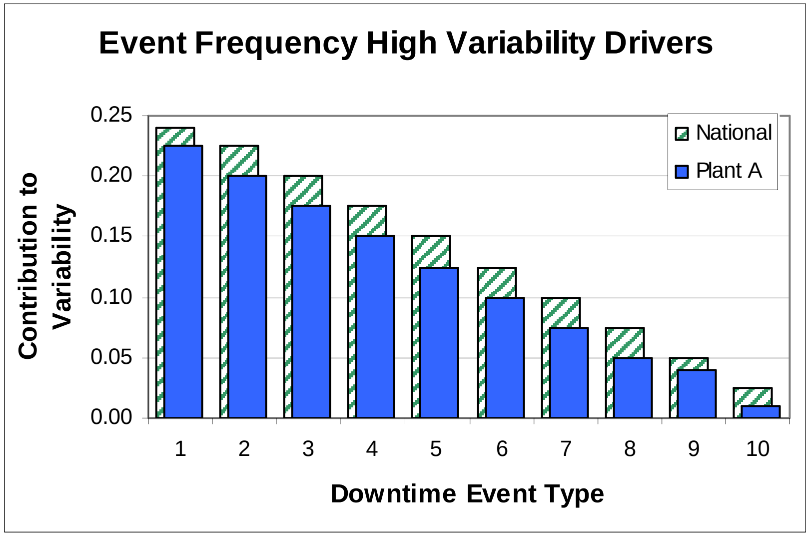
Figure B-20: Operational Unavailability High Variability Drivers – Rollup, All Data



	Downtime Event Type
1	Component A
2	Component B
3	Component C
4	Component D
5	Component E
6	Component F
7	Component G
8	Component H
9	Component I
10	Component J

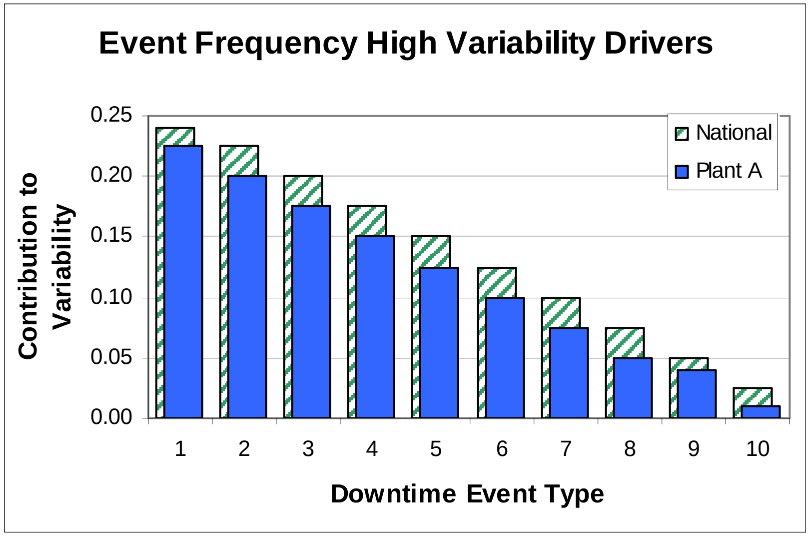
Figure B-21: Operational Unavailability High Variability Drivers – Rollup, 1/1-6/30/2008

Event Frequency (MTBE) High Variability Drivers – Rollup



Downtime Event Type	
1	Component A
2	Component B
3	Component C
4	Component D
5	Component E
6	Component F
7	Component G
8	Component H
9	Component I
10	Component J

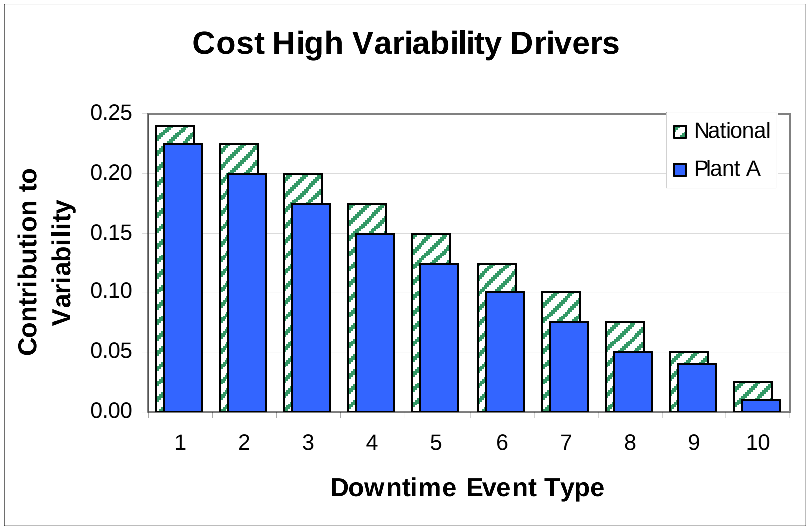
Figure B-22: Event Frequency High Variability Drivers – Rollup, All Data



Downtime Event Type	
1	Component A
2	Component B
3	Component C
4	Component D
5	Component E
6	Component F
7	Component G
8	Component H
9	Component I
10	Component J

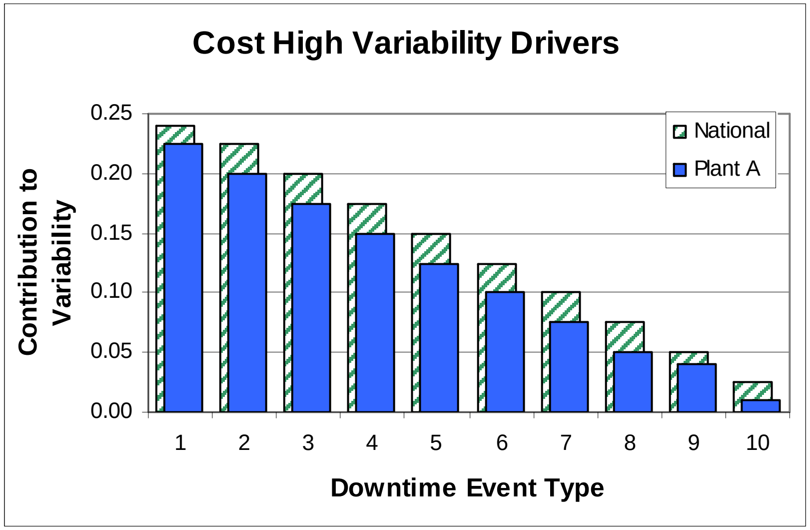
Figure B-23: Event Frequency High Variability Drivers – Rollup, 1/1-6/30/2008

Cost High Variability Drivers – Rollup



Downtime Event Type	
1	Component A
2	Component B
3	Component C
4	Component D
5	Component E
6	Component F
7	Component G
8	Component H
9	Component I
10	Component J

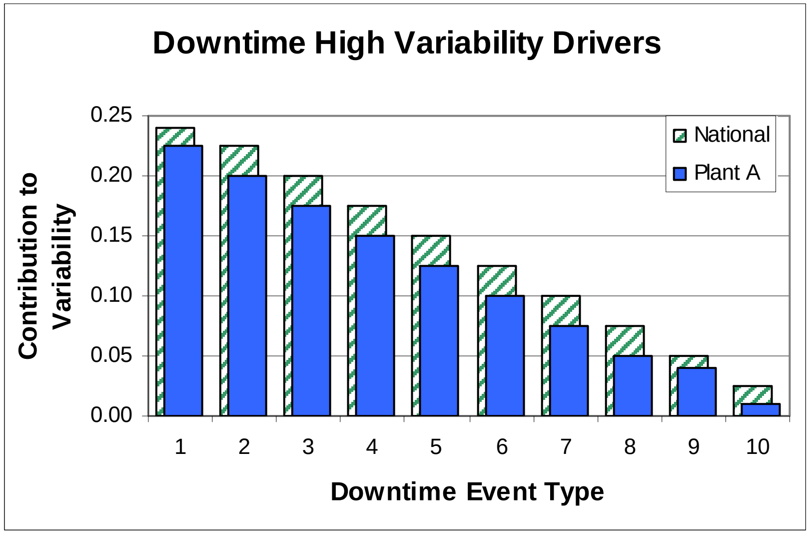
Figure B-24: Cost High Variability Drivers – Rollup, All Data



Downtime Event Type	
1	Component A
2	Component B
3	Component C
4	Component D
5	Component E
6	Component F
7	Component G
8	Component H
9	Component I
10	Component J

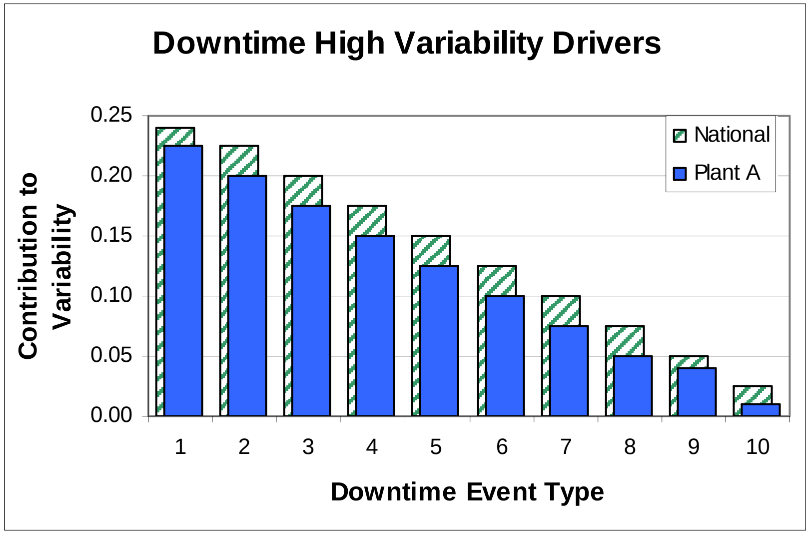
Figure B-25: Cost High Variability Drivers – Rollup, 1/1-6/30/2008

Downtime High Variability Drivers – Rollup



Downtime Event Type	
1	Component A
2	Component B
3	Component C
4	Component D
5	Component E
6	Component F
7	Component G
8	Component H
9	Component I
10	Component J

Figure B-26: Downtime High Variability Drivers – Rollup, All Data



Downtime Event Type	
1	Component A
2	Component B
3	Component C
4	Component D
5	Component E
6	Component F
7	Component G
8	Component H
9	Component I
10	Component J

Figure B-27: Downtime High Variability Drivers – Rollup, 1/1-6/30/2008

Low Variability Drivers – Roll Up

Variability drivers are events which affect the uncertainty in reliability metrics. The following figures illustrate the drivers (rolled up to the second level of detail in the taxonomy) that contribute the most to overall certainty in the metric listed. Only drivers that occurred on more than 1 turbine are shown.

Operational Unavailability Low Variability Drivers – Rollup

Component AA
Component BB
Component CC
Component DD
Component EE
Component FF
Component GG
Component HH
Component II
Component JJ
Component KK
Component LL
Component MM
Component NN
Component OO
Component PP
Component QQ
Component RR
Component SS
Component TT

Table B-2: Plant Operational Unavailability Low Variability Drivers – Rollup, All Data

Component AA
Component BB
Component CC
Component DD
Component EE
Component FF
Component GG
Component HH
Component II
Component JJ
Component KK
Component LL
Component MM
Component NN
Component OO
Component PP
Component QQ
Component RR
Component SS
Component TT

Table B-3: Plant Operational Unavailability Low Variability Drivers – Rollup, 1/1-6/30/2008

Event Frequency (MTBE) Low Variability Drivers – Rollup

Component AA
Component BB
Component CC
Component DD
Component EE
Component FF
Component GG
Component HH
Component II
Component JJ
Component KK
Component LL
Component MM
Component NN
Component OO
Component PP
Component QQ
Component RR
Component SS
Component TT

Table B-4: Plant Event Frequency Low Variability Drivers – Rollup, All Data

Component AA
Component BB
Component CC
Component DD
Component EE
Component FF
Component GG
Component HH
Component II
Component JJ
Component KK
Component LL
Component MM
Component NN
Component OO
Component PP
Component QQ
Component RR
Component SS
Component TT

Table B-5: Plant Event Frequency Low Variability Drivers – Rollup, 1/1-6/30/2008

Cost Low Variability Drivers – Rollup

Component AA
Component BB
Component CC
Component DD
Component EE
Component FF
Component GG
Component HH
Component II
Component JJ
Component KK
Component LL
Component MM
Component NN
Component OO
Component PP
Component QQ
Component RR
Component SS
Component TT

Table B-6: Plant Cost Low Variability Drivers – Rollup, All Data

Component AA
Component BB
Component CC
Component DD
Component EE
Component FF
Component GG
Component HH
Component II
Component JJ
Component KK
Component LL
Component MM
Component NN
Component OO
Component PP
Component QQ
Component RR
Component SS
Component TT

Table B-7: Plant Cost Low Variability Drivers – Rollup, 1/1-6/30/2008

Downtime Low Variability Drivers – Rollup

Component AA
Component BB
Component CC
Component DD
Component EE
Component FF
Component GG
Component HH
Component II
Component JJ
Component KK
Component LL
Component MM
Component NN
Component OO
Component PP
Component QQ
Component RR
Component SS
Component TT

Table B-8: Plant Downtime Low Variability Drivers – Rollup, All Data

Component AA
Component BB
Component CC
Component DD
Component EE
Component FF
Component GG
Component HH
Component II
Component JJ
Component KK
Component LL
Component MM
Component NN
Component OO
Component PP
Component QQ
Component RR
Component SS
Component TT

Table B-9: Plant Downtime Low Variability Drivers – Rollup, 1/1-6/30/2008

Turbine Summary

Turbine	Operational Availability	Mean Time Between Events (hours)	Average Cost Per Event	Mean Downtime Per Event (hours)
Turbine 0001	X%	X	$X	X
Turbine 0002	X%	X	$X	X
Turbine 0003	X%	X	$X	X
Turbine 0004	X%	X	$X	X
Turbine 0005	X%	X	$X	X
Turbine 0006	X%	X	$X	X
Turbine 0007	X%	X	$X	X
Turbine 0008	X%	X	$X	X
Turbine 0009	X%	X	$X	X
Turbine 0010	X%	X	$X	X
…	…	…	…	…

Table B-10: Turbine Summary Statistics – All Data

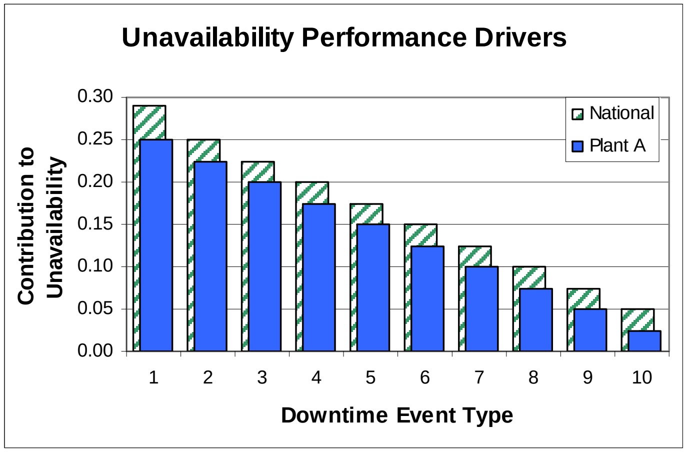
Turbine	Operational Availability	Mean Time Between Events (hours)	Average Cost Per Event	Mean Downtime Per Event (hours)
Turbine 0001	X%	X	$X	X
Turbine 0002	X%	X	$X	X
Turbine 0003	X%	X	$X	X
Turbine 0004	X%	X	$X	X
Turbine 0005	X%	X	$X	X
Turbine 0006	X%	X	$X	X
Turbine 0007	X%	X	$X	X
Turbine 0008	X%	X	$X	X
Turbine 0009	X%	X	$X	X
Turbine 0010	X%	X	$X	X
…	…	…	…	…

Table B-11: Turbine Summary Statistics – 1/1-6/30/2008

Appendix A: Performance Drivers – Full Taxonomy

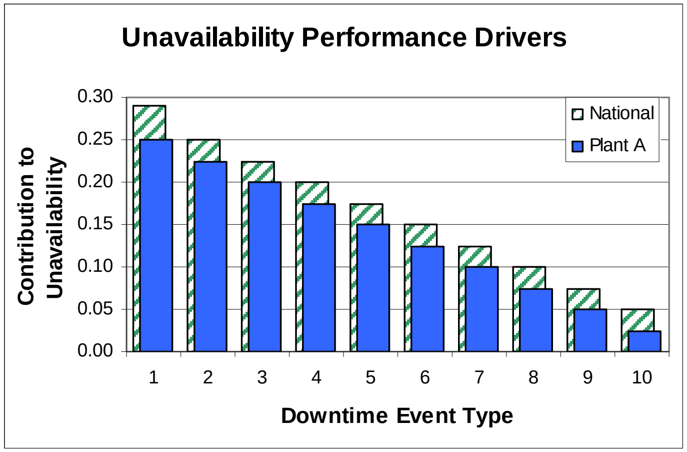
Performance drivers are events which affect reliability metrics. The following figures illustrate the performance drivers (using the full level of detail in the taxonomy[2]) with the most significant negative effect on the metric listed.

Operational Unavailability Performance Drivers – Full Taxonomy



Downtime Event Type	
1	Component A
2	Component B
3	Component C
4	Component D
5	Component E
6	Component F
7	Component G
8	Component H
9	Component I
10	Component J

Figure B-28: Operational Unavailability Performance Drivers – All Data

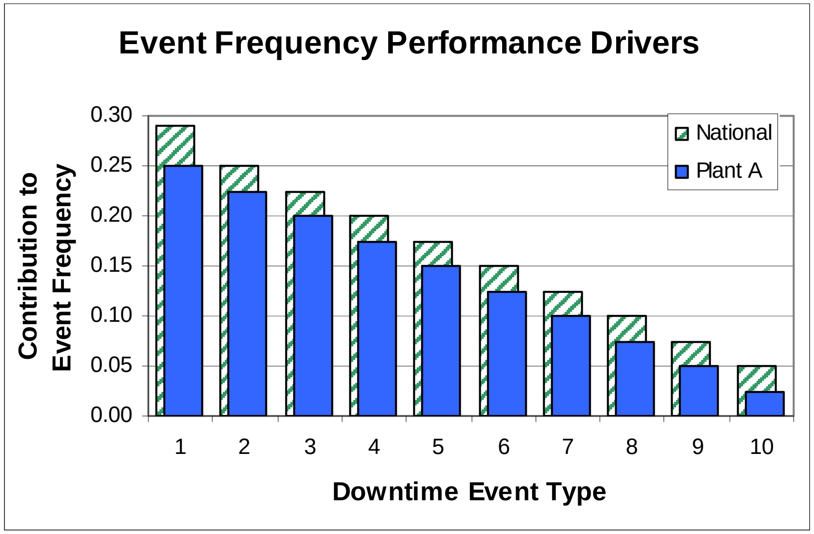


Downtime Event Type	
1	Component A
2	Component B
3	Component C
4	Component D
5	Component E
6	Component F
7	Component G
8	Component H
9	Component I
10	Component J

Figure B-29: Operational Unavailability Performance Drivers – 1/1-6/30/2008

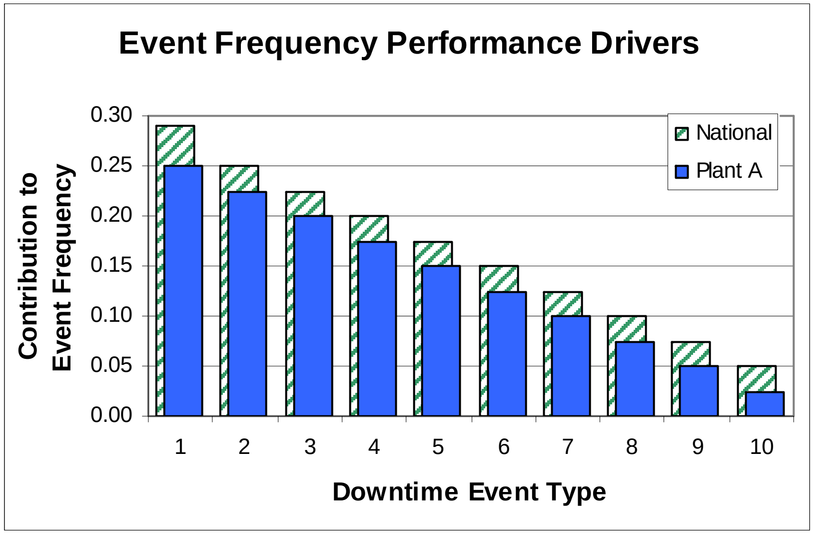
[2] See User's Guide for illustration of taxonomy.

Event Frequency (MTBE) Performance Drivers – Full Taxonomy



Downtime Event Type	
1	Component A
2	Component B
3	Component C
4	Component D
5	Component E
6	Component F
7	Component G
8	Component H
9	Component I
10	Component J

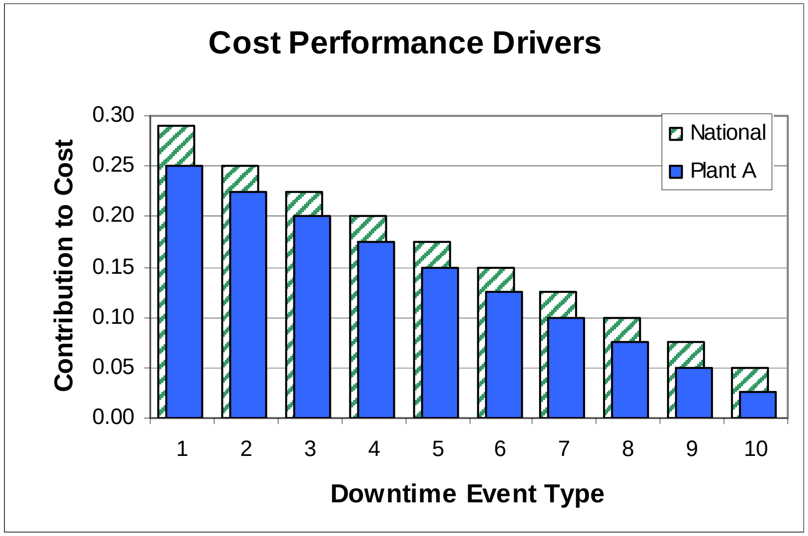
Figure B-30: Event Frequency Performance Drivers – All Data



Downtime Event Type	
1	Component A
2	Component B
3	Component C
4	Component D
5	Component E
6	Component F
7	Component G
8	Component H
9	Component I
10	Component J

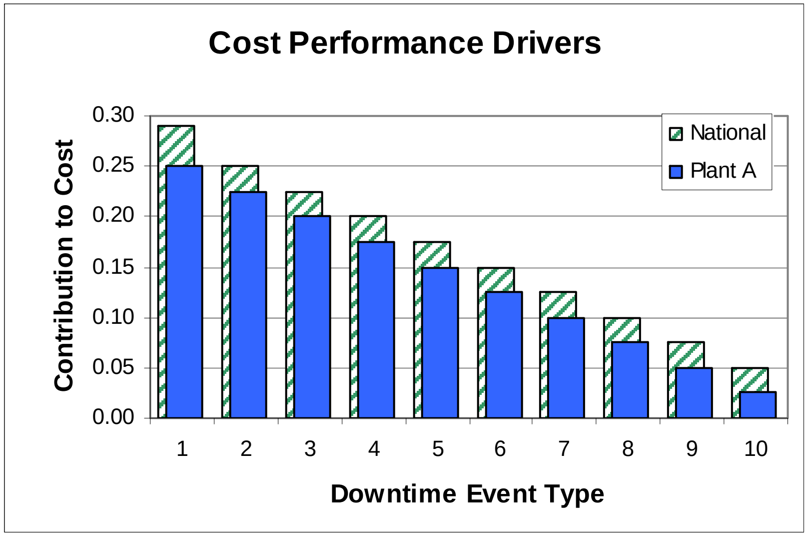
Figure B-31: Event Frequency Performance Drivers – 1/1-6/30/2008

Cost Performance Drivers – Full Taxonomy



Downtime Event Type	
1	Component A
2	Component B
3	Component C
4	Component D
5	Component E
6	Component F
7	Component G
8	Component H
9	Component I
10	Component J

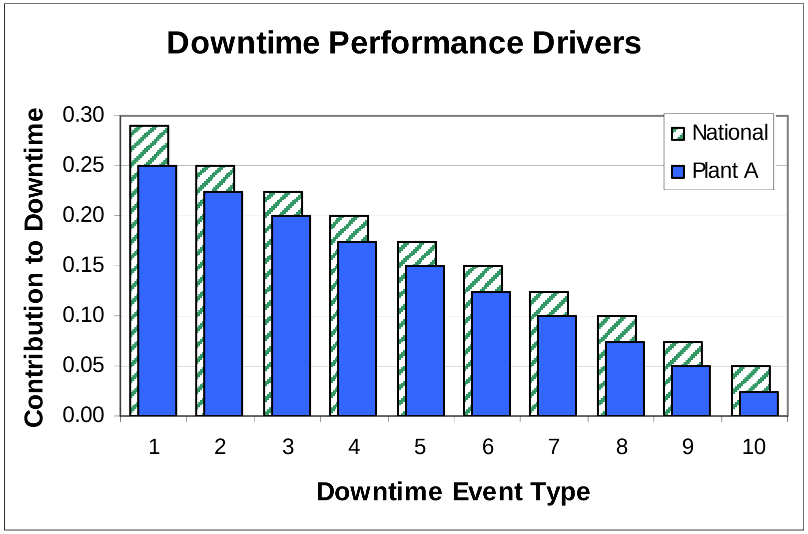
Figure B-32: Cost Performance Drivers – All Data



Downtime Event Type	
1	Component A
2	Component B
3	Component C
4	Component D
5	Component E
6	Component F
7	Component G
8	Component H
9	Component I
10	Component J

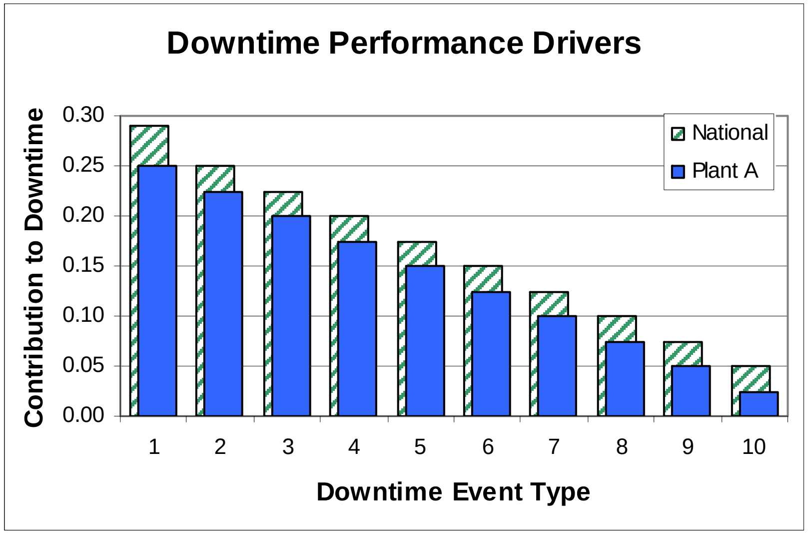
Figure B-33: Cost Performance Drivers – 1/1-6/30/2008

Downtime Performance Drivers – Full Taxonomy



Downtime Event Type	
1	Component A
2	Component B
3	Component C
4	Component D
5	Component E
6	Component F
7	Component G
8	Component H
9	Component I
10	Component J

Figure B-34: Downtime Performance Drivers – All Data



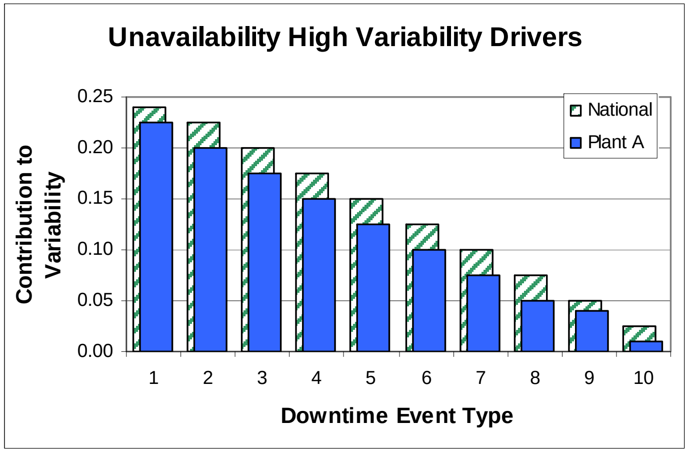
Downtime Event Type	
1	Component A
2	Component B
3	Component C
4	Component D
5	Component E
6	Component F
7	Component G
8	Component H
9	Component I
10	Component J

Figure B-35: Downtime Performance Drivers – 1/1-6/30/2008

Appendix B: High Variability Drivers – Full Taxonomy

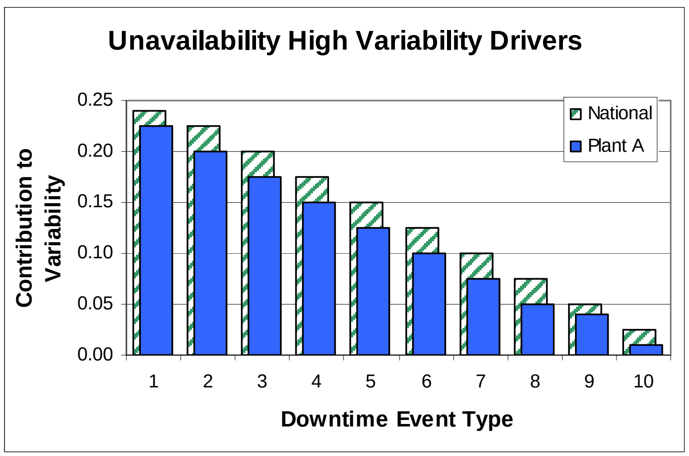
Variability drivers are events which affect the uncertainty in reliability metrics. The following figures illustrate the variability drivers (using the full level of detail in the taxonomy) with the most significant negative effect on the certainty of the metric listed.

Operational Unavailability High Variability Drivers – Full Taxonomy



Downtime Event Type	
1	Component A
2	Component B
3	Component C
4	Component D
5	Component E
6	Component F
7	Component G
8	Component H
9	Component I
10	Component J

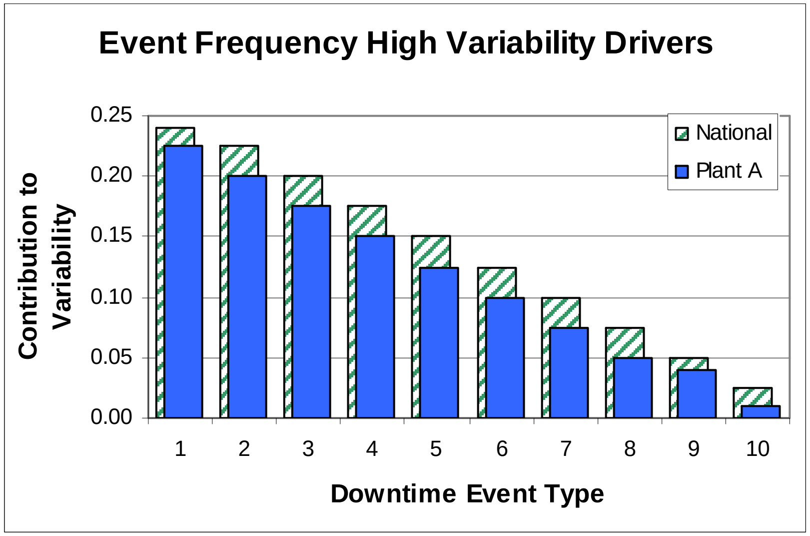
Figure B-36: Operational Unavailability High Variability Drivers – All Data



Downtime Event Type	
1	Component A
2	Component B
3	Component C
4	Component D
5	Component E
6	Component F
7	Component G
8	Component H
9	Component I
10	Component J

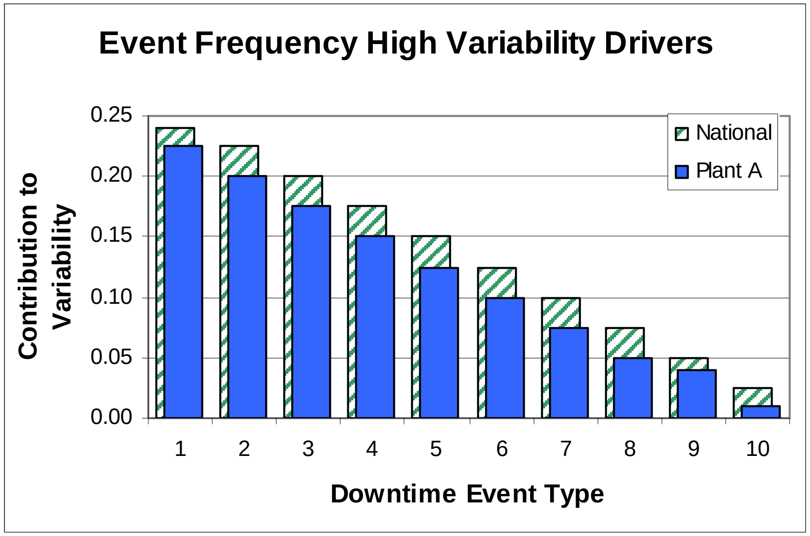
Figure B-37: Operational Unavailability High Variability Drivers – 1/1-6/30/2008

Event Frequency (MTBE) High Variability Drivers – Full Taxonomy



Downtime Event Type	
1	Component A
2	Component B
3	Component C
4	Component D
5	Component E
6	Component F
7	Component G
8	Component H
9	Component I
10	Component J

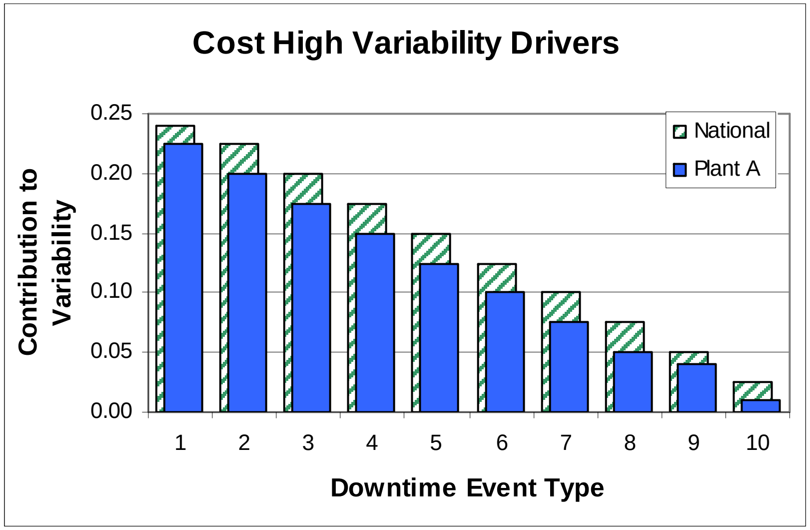
Figure B-38: Event Frequency High Variability Drivers – All Data



Downtime Event Type	
1	Component A
2	Component B
3	Component C
4	Component D
5	Component E
6	Component F
7	Component G
8	Component H
9	Component I
10	Component J

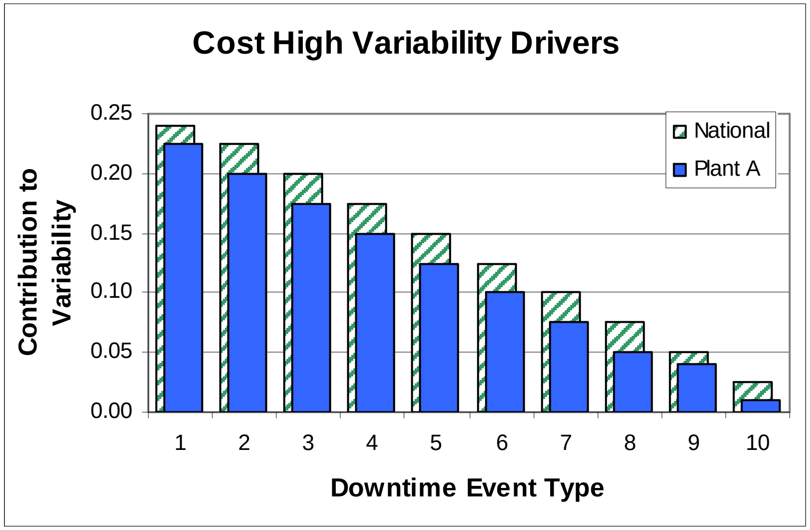
Figure B-39: Event Frequency High Variability Drivers – 1/1-6/30/2008

Cost High Variability Drivers – Full Taxonomy



Downtime Event Type	
1	Component A
2	Component B
3	Component C
4	Component D
5	Component E
6	Component F
7	Component G
8	Component H
9	Component I
10	Component J

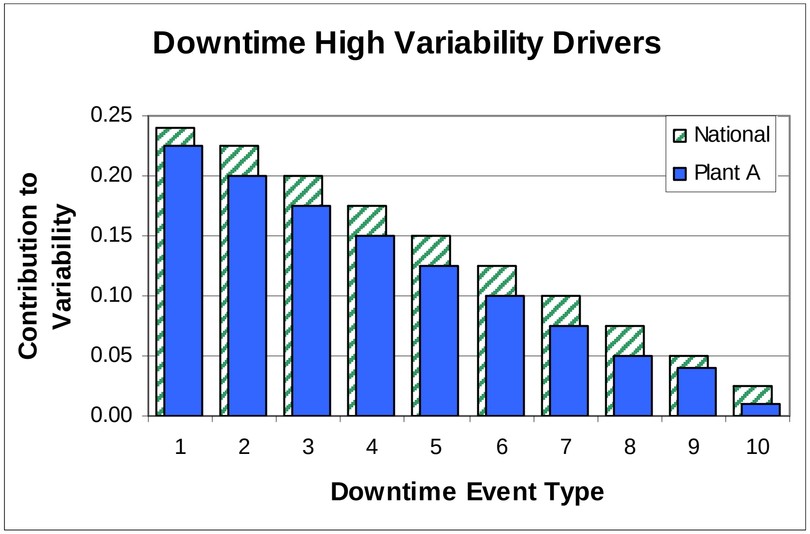
Figure B-40: Cost High Variability Drivers – All Data



Downtime Event Type	
1	Component A
2	Component B
3	Component C
4	Component D
5	Component E
6	Component F
7	Component G
8	Component H
9	Component I
10	Component J

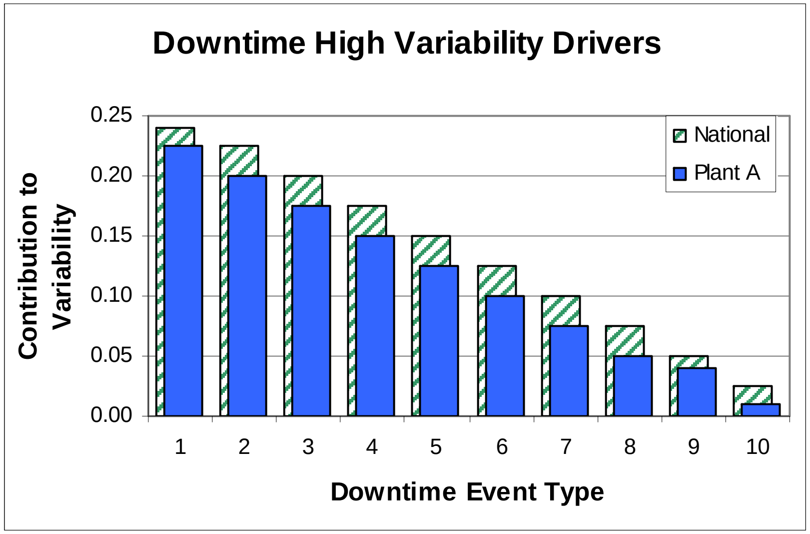
Figure B-41: Cost High Variability Drivers – 1/1-6/30/2008

Downtime High Variability Drivers – Full Taxonomy



Downtime Event Type	
1	Component A
2	Component B
3	Component C
4	Component D
5	Component E
6	Component F
7	Component G
8	Component H
9	Component I
10	Component J

Figure B-42: Downtime High Variability Drivers – All Data



Downtime Event Type	
1	Component A
2	Component B
3	Component C
4	Component D
5	Component E
6	Component F
7	Component G
8	Component H
9	Component I
10	Component J

Figure B-43: Downtime High Variability Drivers – 1/1-6/30/2008

Appendix C: Low Variability Drivers – Full Taxonomy

Variability drivers are events which affect the uncertainty in reliability metrics. The following table lists the drivers (using the full level of detail in the taxonomy) that contribute most to overall certainty in the certainty of the metric listed. Only drivers that occurred on more than 1 turbine are shown.

Operational Unavailability Low Variability Drivers – Full Taxonomy

Component AA
Component BB
Component CC
Component DD
Component EE
Component FF
Component GG
Component HH
Component II
Component JJ
Component KK
Component LL
Component MM
Component NN
Component OO
Component PP
Component QQ
Component RR
Component SS
Component TT

Table B-12: Plant Operational Unavailability Low Variability Drivers – All Data

Component AA
Component BB
Component CC
Component DD
Component EE
Component FF
Component GG
Component HH
Component II
Component JJ
Component KK
Component LL
Component MM
Component NN
Component OO
Component PP
Component QQ
Component RR
Component SS
Component TT

Table B-13: Plant Operational Unavailability Low Variability Drivers – 1/1-6/30/2008

Event Frequency (MTBE) Low Variability Drivers – Full Taxonomy

Component AA
Component BB
Component CC
Component DD
Component EE
Component FF
Component GG
Component HH
Component II
Component JJ
Component KK
Component LL
Component MM
Component NN
Component OO
Component PP
Component QQ
Component RR
Component SS
Component TT

Table B-14: Plant Event Frequency Low Variability Drivers – All Data

Component AA
Component BB
Component CC
Component DD
Component EE
Component FF
Component GG
Component HH
Component II
Component JJ
Component KK
Component LL
Component MM
Component NN
Component OO
Component PP
Component QQ
Component RR
Component SS
Component TT

Table B-15: Plant Event Frequency Low Variability Drivers – 1/1-6/30/2008

Cost Low Variability Drivers – Full Taxonomy

Component AA
Component BB
Component CC
Component DD
Component EE
Component FF
Component GG
Component HH
Component II
Component JJ
Component KK
Component LL
Component MM
Component NN
Component OO
Component PP
Component QQ
Component RR
Component SS
Component TT

Table B-16: Plant Cost Low Variability Drivers – All Data

Component AA
Component BB
Component CC
Component DD
Component EE
Component FF
Component GG
Component HH
Component II
Component JJ
Component KK
Component LL
Component MM
Component NN
Component OO
Component PP
Component QQ
Component RR
Component SS
Component TT

Table B-17: Plant Cost Low Variability Drivers – 1/1-6/30/2008

Downtime Low Variability Drivers – Full Taxonomy

Component AA
Component BB
Component CC
Component DD
Component EE
Component FF
Component GG
Component HH
Component II
Component JJ
Component KK
Component LL
Component MM
Component NN
Component OO
Component PP
Component QQ
Component RR
Component SS
Component TT

Table B-18: Plant Downtime Low Variability Drivers – All Data

Component AA
Component BB
Component CC
Component DD
Component EE
Component FF
Component GG
Component HH
Component II
Component JJ
Component KK
Component LL
Component MM
Component NN
Component OO
Component PP
Component QQ
Component RR
Component SS
Component TT

Table B-19: Plant Downtime Low Variability Drivers – 1/1-6/30/2008

Appendix D: Taxonomy & Failure Mode Summary

Event Type	Yearly Event Rate[3]	Mean Downtime[4]	Cost/ Event	Downtime Cost/Hr
Balance of Structure-Mx	X	X	$X	$X
Balance of Structure-Rst	X	X	$X	$X
Balance of Structure-Sch	X	X	$X	$X
Brake::Mechanical brakes	X	X	$X	$X
Brake::Mechanical brakes-Mx	X	X	$X	$X
Brake::Mechanical brakes-Sch	X	X	$X	$X
Brake::Parking Brake - manual transmission lock-Mx	X	X	$X	$X
Brake-Mx	X	X	$X	$X
Brake-Rst	X	X	$X	$X
Control system	X	X	$X	$X
Control system::Anemometer	X	X	$X	$X
Control system::Anemometer-Mx	X	X	$X	$X
Control system::Anemometer-Rst	X	X	$X	$X
Control system::Anemometer-Sch	X	X	$X	$X
Control system::Control SCADA	X	X	$X	$X
Control system::Control SCADA-Mx	X	X	$X	$X
Control system::Control SCADA-Sch	X	X	$X	$X
Control system::PLC	X	X	$X	$X
Control system::PLC-Mx	X	X	$X	$X
Control system::PLC-Rst	X	X	$X	$X
Control system::PLC-Sch	X	X	$X	$X
Control system::Sensors(static)	X	X	$X	$X
Control system::Sensors(static)-Mx	X	X	$X	$X
Control system::Sensors(static)-Rst	X	X	$X	$X
Control system::UPS	X	X	$X	$X
Control system::UPS-Mx	X	X	$X	$X
Control system::UPS-Rst	X	X	$X	$X
Control system::Wind vane-Mx	X	X	$X	$X
Control system-Mx	X	X	$X	$X
Control system-Rst	X	X	$X	$X
Control system-Sch	X	X	$X	$X
Drive Train-Mx	X	X	$X	$X
Electrical	X	X	$X	$X
Electrical::Circuit breakers and switches	X	X	$X	$X
Electrical::Circuit breakers and switches-Mx	X	X	$X	$X
Electrical::Circuit breakers and switches-Rst	X	X	$X	$X
Electrical::Circuit breakers and switches-Sch	X	X	$X	$X
Electrical::Crowbar	X	X	$X	$X
Electrical::Crowbar-Mx	X	X	$X	$X
Electrical::Crowbar-Rst	X	X	$X	$X
Electrical::Crowbar-Sch	X	X	$X	$X

[3] Yearly Event Rate is the expected number of events per turbine per calendar year.
[4] Mean Downtime is the expected number of hours of downtime for a single event.

Event Type	Yearly Event Rate[3]	Mean Downtime[4]	Cost/ Event	Downtime Cost/Hr
Electrical::Main circuit breaker	X	X	$X	$X
Electrical::Main circuit breaker-Mx	X	X	$X	$X
Electrical::Main circuit breaker-Rst	X	X	$X	$X
Electrical::Main circuit breaker-Sch	X	X	$X	$X
Electrical::Main contactor-Mx	X	X	$X	$X
Electrical::Metering and relays-Mx	X	X	$X	$X
Electrical::Pad mounted transformer-Mx	X	X	$X	$X
Electrical::Pad mounted transformer-Rst	X	X	$X	$X
Electrical::Pad mounted transformer-Sch	X	X	$X	$X
Electrical::Power converters-Mx	X	X	$X	$X
Electrical::Soft starter-Mx	X	X	$X	$X
Electrical::Substation-Mx	X	X	$X	$X
Electrical::Substation-Rst	X	X	$X	$X
Electrical::Switchgear	X	X	$X	$X
Electrical::Switchgear-Mx	X	X	$X	$X
Electrical::Switchgear-Rst	X	X	$X	$X
Electrical::Switchgear-Sch	X	X	$X	$X
Electrical::Transformer-Mx	X	X	$X	$X
Electrical::Transformer-Rst	X	X	$X	$X
Electrical::Transformer-Sch	X	X	$X	$X
Electrical-Mx	X	X	$X	$X
Electrical-Rst	X	X	$X	$X
Electrical-Sch	X	X	$X	$X
Emergency stop-Mx	X	X	$X	$X
Emergency stop-Rst	X	X	$X	$X
GearBox::Bearings	X	X	$X	$X
GearBox::Bearings-Mx	X	X	$X	$X
GearBox::Bearings-Rst	X	X	$X	$X
GearBox::Bearings-Sch	X	X	$X	$X
GearBox::Gearbox casing-Mx	X	X	$X	$X
GearBox::Gearbox casing-Rst	X	X	$X	$X
GearBox::Gearbox oil system	X	X	$X	$X
GearBox::Gearbox oil system-Mx	X	X	$X	$X
GearBox::Gearbox oil system-Rst	X	X	$X	$X
GearBox::Gearbox oil system-Sch	X	X	$X	$X
GearBox::Gears-Rst	X	X	$X	$X
GearBox::High speed shaft-Mx	X	X	$X	$X
GearBox::High speed shaft-Rst	X	X	$X	$X
GearBox-Mx	X	X	$X	$X
GearBox-Rst	X	X	$X	$X
GearBox-Sch	X	X	$X	$X
Generator	X	X	$X	$X
Generator::Commutator and brushes	X	X	$X	$X
Generator::Commutator and brushes-Mx	X	X	$X	$X
Generator::Commutator and brushes-Rst	X	X	$X	$X
Generator::Commutator and brushes-Sch	X	X	$X	$X

Event Type	Yearly Event Rate[3]	Mean Downtime[4]	Cost/ Event	Downtime Cost/Hr
Generator::Contactor	X	X	$X	$X
Generator::Contactor-Mx	X	X	$X	$X
Generator::Converter	X	X	$X	$X
Generator::Converter-Mx	X	X	$X	$X
Generator::Converter-Rst	X	X	$X	$X
Generator::Converter-Sch	X	X	$X	$X
Generator::Encoder	X	X	$X	$X
Generator::Encoder-Mx	X	X	$X	$X
Generator::Encoder-Rst	X	X	$X	$X
Generator::Encoder-Sch	X	X	$X	$X
Generator::Exciter-Sch	X	X	$X	$X
Generator::Generator bearings	X	X	$X	$X
Generator::Generator bearings-Mx	X	X	$X	$X
Generator::Generator bearings-Sch	X	X	$X	$X
Generator::Generator cooling system	X	X	$X	$X
Generator::Generator cooling system-Mx	X	X	$X	$X
Generator::Generator cooling system-Rst	X	X	$X	$X
Generator::Generator shaft-Mx	X	X	$X	$X
Generator::Insulation-Mx	X	X	$X	$X
Generator::Overspeed sensor	X	X	$X	$X
Generator::Overspeed sensor-Mx	X	X	$X	$X
Generator::Overspeed sensor-Rst	X	X	$X	$X
Generator::Wiring/Cables-Mx	X	X	$X	$X
Generator::Wiring/Cables-Rst	X	X	$X	$X
Generator::Wiring/Cables-Sch	X	X	$X	$X
Generator-Mx	X	X	$X	$X
Generator-Rst	X	X	$X	$X
Generator-Sch	X	X	$X	$X
Maintenance::Maintenance (12-month)-Sch	X	X	$X	$X
Maintenance::Maintenance (18-month)-Sch	X	X	$X	$X
Maintenance::Maintenance (3-month)-Sch	X	X	$X	$X
Maintenance::Maintenance (6-month)-Sch	X	X	$X	$X
Maintenance::Testing-Mx	X	X	$X	$X
Maintenance-Sch	X	X	$X	$X
Met Tower::Wind vane-Rst	X	X	$X	$X
Met Tower-Mx	X	X	$X	$X
Pitch system::Blade pitch bearing-Mx	X	X	$X	$X
Pitch system::Embedded control system	X	X	$X	$X
Pitch system::Embedded control system-Mx	X	X	$X	$X
Pitch system::Embedded control system-Rst	X	X	$X	$X
Pitch system::Pitch hydraulics	X	X	$X	$X
Pitch system::Pitch hydraulics-Mx	X	X	$X	$X
Pitch system::Pitch hydraulics-Rst	X	X	$X	$X
Pitch system::Pitch hydraulics-Sch	X	X	$X	$X
Pitch system-Mx	X	X	$X	$X
Pitch system-Rst	X	X	$X	$X

Event Type	Yearly Event Rate[3]	Mean Downtime[4]	Cost/ Event	Downtime Cost/Hr
Rotor	X	X	$X	$X
Rotor::Blade	X	X	$X	$X
Rotor::Blade-Mx	X	X	$X	$X
Rotor::Blade-Rst	X	X	$X	$X
Rotor::Blade-Sch	X	X	$X	$X
Rotor::De-icing system-Mx	X	X	$X	$X
Rotor::De-icing system-Rst	X	X	$X	$X
Rotor::Hub-Mx	X	X	$X	$X
Rotor::Hub-Sch	X	X	$X	$X
Rotor::Root attachment-Sch	X	X	$X	$X
Rotor-Mx	X	X	$X	$X
Slip Rings	X	X	$X	$X
Slip Rings-Sch	X	X	$X	$X
Structure::Foundation-Sch	X	X	$X	$X
Structure::Nacelle	X	X	$X	$X
Structure::Nacelle-Mx	X	X	$X	$X
Structure::Nacelle-Rst	X	X	$X	$X
Structure::Nacelle-Sch	X	X	$X	$X
Structure::Tower-Mx	X	X	$X	$X
Structure::Tower-Sch	X	X	$X	$X
Structure-Mx	X	X	$X	$X
Structure-Rst	X	X	$X	$X
Structure-Sch	X	X	$X	$X
Unidentified Failure-Mx	X	X	$X	$X
Unidentified Fault-Rst	X	X	$X	$X
Yaw System::Yaw bearing-Mx	X	X	$X	$X
Yaw System::Yaw brake-Mx	X	X	$X	$X
Yaw System::Yaw brake-Rst	X	X	$X	$X
Yaw System::Yaw control system	X	X	$X	$X
Yaw System::Yaw control system-Mx	X	X	$X	$X
Yaw System::Yaw control system-Rst	X	X	$X	$X
Yaw System::Yaw lubrication system-Mx	X	X	$X	$X
Yaw System::Yaw motor/hydraulics	X	X	$X	$X
Yaw System::Yaw motor/hydraulics-Mx	X	X	$X	$X
Yaw System::Yaw motor/hydraulics-Rst	X	X	$X	$X
Yaw System-Mx	X	X	$X	$X
Yaw System-Rst	X	X	$X	$X

Table B-20: Event Type Summary

Appendix C: Pro-Opta

Sandia has been heavily involved in modeling, simulation, and optimization of system reliability, maintainability, and availability for many years. The Pro-Opta software package is a reliability analysis and optimization program developed by Sandia National Laboratories. Pro-Opta is intended to provide information needed to make strategic decisions in the competitive marketplace. It has been shown that not only can Pro-Opta provide valuable information in the estimation of fleet performance using existing failure and repair data, but this data can also be mined for additional information of significant value. Pro-Opta can provide guidance regarding investment strategies that result in fleet availability levels superior to those achievable without supporting analysis (Sand 2006-7218).

The following few paragraphs describe the basic purpose of each of the six Pro-Opta modules. (Additional information about Pro-Opta can be found in the Pro-Opta User Manuals, which come installed with the Pro-Opta software.)

Import Setup

The importation of field data into Data Analyzer requires a Pro-Opta configuration file. Pro-Opta has a default configuration that might serve the requirements for importing your field data. If not, a configuration built specifically for your field data can be generated using Import Setup. Thus, running Import Setup is often a preparatory step towards importing field data into Data Analyzer. It links the internal Pro-Opta field names to your preferred terminology. It also allows you to select the fields to include in the analysis and to select the types of analysis results to generate.

Data Analyzer

Data Analyzer imports field data and analyzes the data according to the configuration you select. In order to use Data Analyzer the field data must contain records of the failure events that occurred on your equipment. Each record must define which machine went down, the date and time of the event, a specific and unique reason why the event occurred (known as a failure mode), and how long the machine was down, in hours. Data Analyzer analyzes this equipment failure event data in several ways. It is easy to determine which types of events and which machines are causing the most problems. This helps you make better judgments as to which areas you should focus on to best improve reliability. An optimization study can be built on a model generated by Data Analyzer.

Data Manager

Use the Data Manager to build a Pro-Opta failure mode library. Such a library is required for Pro-Opta design analysis. Entering failure mode data is similar to entering data onto a spreadsheet. If you are more comfortable using a spreadsheet, enter the data there and import it to Data Manager. There are a few required properties for each failure mode: Failure Mode ID, Failure Mode Name, nominal failure rate or nominal failure probability, and nominal downtime. It is likely that there is uncertainty or variability in the values for failure rates, downtimes, and failure probabilities. To capture this uncertainty, you are encouraged to assign probability distributions to these properties. Guidance on the selection of distribution type is provided in the Pro-Opta Design Manual. The selection depends on how much supporting data you have.

Fault Tree Interface

Whether analyzing a new design or an existing system, use the Fault Tree Interface to enter your fault tree for use by Pro-Opta. Begin by assigning a name to the top event that is appropriate for system failure. From there construct the tree by successively defining the children of each event using the immediate cause concept. It is in this interface where cost information can be input and correlations amongst failure modes can be defined. The Fault Tree Interface analyzes a fault tree in two steps. First, it uses the laws of Boolean algebra to express an equivalent failure equation in disjunctive form, known traditionally as a collection of cutsets. Second, using the properties of the associated failure mode library and any cost and correlation information, the Fault Tree Interface quantifies a set of performance measures for the fault tree. View the results of the fault tree analysis using the Results Module.

Results Module

The Results Module provides various ways to examine system performance measures (MTBF, availability, downtime, reliability, failure probability, and cost). It is most useful when the failure modes have been assigned probability distributions. In that case the performance measures are examined in a statistical framework. The display of the values that a performance measure takes on can be either in tabular form (summary statistics, the raw data) or graphical form (histograms, cumulative distribution functions, Pareto charts). The primary events that are most important in determining the magnitude of the performance measure can be found under the Sensitivity menu. The primary events that are most important in determining the uncertainty in the performance measure can be found under the Uncertainty menu.

Optimizer

Optimizer is designed to perform reliability and spare parts optimizations. Performance optimization determines the best set of modifications or component upgrades to improve equipment reliability within the reliability and cost constraints specified by the user. For performance analysis, Optimizer operates on models developed by Data Analyzer or Fault Tree Interface, or a group of the latter. Spare Parts optimization determines the best set of spare parts to keep on hand, improving equipment availability within the downtime and cost constraints specified by the user. For spares analysis, Optimizer operates on models developed by Data Analyzer or Fault Tree Interface, or directly on a file of demand rates.

Appendix D: Blade Reliability Survey

In April 2008 a blade reliability survey was conducted by phone representing four plants with over 400 turbines, most of which had been in service over three years. Results are as follows:

- **Around 18 years MTBF per turbine**
  - **Highly variable – MTBF per blade is between 15 and 600 years**
  - **Anecdotal stories of all blades failing**
- **About 80 blade replacements – 40 (half) at one plant**
- **Replacement times range from 2 weeks to 2 months**

Blade issues cited include:

- **Manufacturing issues – waviness and overlaid laminates**
- **Bad bonds, delamination, and voids**
- **Leading edge erosion**
- **Trailing edge splits**
- **Lightning – comments:**
  - At one plant every blade has been struck at least once
  - Many repairs and replacements
  - Scorching and splits
  - Manageable problem (relative to gearboxes)

The following table summarizes the information found in the survey, with one row for each responding plant.

Years of operation	***Number of turbines***	***Type of defect ; number of replacements***	***Comments***
0-5	**100+**	**Lightning**	**Lots of strikes**
5-10	**100+**	**Manufacturing – laminations, voids, leading edge erosion, trailing; 6 blades per year replaced one at a time**	**Every blade struck by lightning once, $100k spent per year on repairs**
0-5	**0-50**	**Delamination, voids; 15 blades replaced**	**Clean every year**
5-10	**100+**	**QC – leading edge erosion, bug fouling; 40 blades replaced**	**Clean when gearboxes are changed**

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