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Wind Turbine Reliability: A Database and Analysis Approach

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Abstract

The US wind Industry has experienced remarkable growth since the turn of the century. At the same time, the physical size and electrical generation capabilities of wind turbines has also experienced remarkable growth. As the market continues to expand, and as wind generation continues to gain a significant share of the generation portfolio, the reliability of wind turbine technology becomes increasingly important.

This report addresses how operations and maintenance costs are related to unreliability—that is the failures experienced by systems and components. Reliability tools are demonstrated, data needed to understand and catalog failure events is described, and practical wind turbine reliability models are illustrated, including preliminary results. This report also presents a continuing process of how to proceed with controlling industry requirements, needs, and expectations related to Reliability, Availability, Maintainability, and Safety. A simply stated goal of this process is to better understand and to improve the operable reliability of wind turbine installations.

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Section 1 - Introduction

There is a recognized need for improved reliability in the design, manufacturing quality, operation, and maintenance of wind turbines. Industry and others have acknowledged the importance of reliability in the continued growth and expansion of markets for wind turbine technology. Reliable operations are critical for the hostile environments where turbines are sited and the impacts of reliability (or unreliability) are broad, ranging from economics to advancement of designs.

The purpose of the Department of Energy's wind turbine reliability effort is to facilitate design improvements and improve operations and reduce maintenance costs, thus reducing financial and technical risks. Sandia National Laboratories' Wind Energy Technology Department has been designated the lead organization to spearhead this effort. Sandia has historically been engaged in system reliability research activities in safety, materials, and fatigue; leveraging broad-based expertise and capabilities evolved from engineering numerous critical systems. The National Renewable Energy Laboratory (NREL) has formed a Gearbox Reliability Collaborative, and has made substantial progress in developing technology and processes to reduce the failure rates of gearboxes, a large source of operations and maintenance (O&M) problems.

Sandia will actively seek industry involvement to collect, analyze, and disseminate reliability and performance data essential for determining fleet reliability issues. Critical performance, design, and evaluation techniques will be shared between stakeholders to facilitate comparative evaluations, and identify critical failure modes and potential weak links. Continuing activity in reliability research and targeted R&D aimed at resolving reliability issues will lead back to improved wind turbine design, as well as operations and maintenance practices.

Detailed objectives of this program are to:

- Establish industry benchmarks for reliability performance
- Identify failure trends
- Document industry reliability improvements over time
- Provide high quality information to support O&M practices
- Improve system performance of wind assets through better asset management practices
- Target efforts to address important component reliability problems

Since the inception of SNL's Wind Reliability Program in FY06, a number of actions have been undertaken to help meet these objectives, including structuring the necessary industry collaborations and the creation of a system to collect, analyze, disseminate, and identify critical failure modes and areas for improvements in system reliability. Activities to date include two Wind Turbine Reliability Workshops in 2006 and 2007 with industry, American Wind Energy Association (AWEA), and Utility Wind Integration Group (UWIG) involvement, site background O&M investigations at selected wind plants, various meetings, and publication of the Wind ***Turbine Reliability: Understanding and Minimizing Wind Turbine Operation and Maintenance Costs,*** Sand2006-1100 report.[1]

Section 2 - Definitions

Reliability is defined as:

> ***"The probability that a product will perform its intended function under stated conditions for a specified period of time"***

It is seen that reliability is a probabilistic concept involving a product's planned use, its operating environment and time. Thus the four elements are:

- Probability
- Intended Functions
- Stated Conditions
- Time

The industry-wide accepted turbine lifetime is 20 years. Thus, the reliability of a turbine is the percentage of time (probability) that turbine will be functioning at full capacity (intended function) during appropriate wind conditions at a site with specified wind resource characterization (stated conditions) for a 20-year life (time).

Reliability specialists use a graphical representation called the bathtub curve, shown in Figure 1 to describe product lifecycle. The bathtub curve consists of three areas: an infant mortality period with a decreasing failure rate followed by a normal life period (also known as "useful life") with a low, relatively constant failure rate and ending with a wear-out period that displays an increasing failure rate.

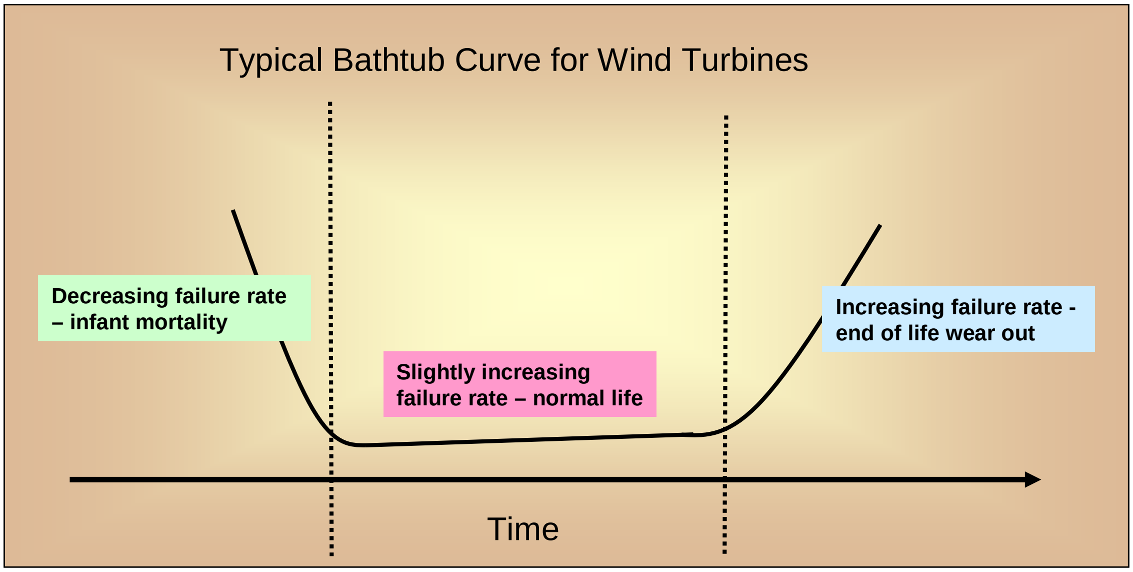


Figure 1. The Bathtub Curve Showing Early (Infant Mortality) Failures, Normal Life, and Wear-Out failures.

A principle system performance measure is system MTBF. The MTBF for a component can be calculated as the total operational hours divided by the number of failures for that component.

MTBF=Operational Time/# of failures

The mean time to repair metric is the average time for a repair or replacement to be made divided by the number of failures for a given component.

MTTR=Total repair time/# of failures

However, it is Availability that is the reliability metric that is most significant in the operations of wind plants. Availability is often expressed as a percentage and it is the amount of time that a system or component is available for use divided by that total amount of time in the period of operation. Another way to state this is the fraction of the "up-time" divided by total time. Up time can be expressed as the mean time to failure (the period when a component is operational), and the total time is the operational period combined with the non-operational period when a component is undergoing a process of repair or replacement.

Availability (A) = MTBF / [MTBF + MTTR+ PM]

Preventative maintenance (PM) is included if it requires component outage. Availability is most closely related to energy production and revenues so it is of paramount importance in the operation of a wind farm.

These reliability metrics are often used in combination with each other. Occasionally, broad reliability parameters are stated in a consolidated manner such as in the performance of a "RAMS Analysis", where Reliability, Availability, Maintainability, and Safety are all addressed together since they are all operational issues. "Maintainability" has a non-numeric definition and is related to the access, clearances, and provisions for repair and replacement items, such as lifting or transporting devices. "Safety" addresses these same aspects, as well as training for these operations in the greater environmental safety and health aspects. It is noted that while safety is given small amount of attention in this report it is number one in terms of importance in O&M activities. Reliability analyses can have a big impact on safety if the number of hazardous actions can be minimized through decreased failure rates and improved reliability.

The following figure 2 is based on the responses of a number of operators surveyed by the Global Energy Concepts Company[2], showing that wind plant availability increases over time (shown as wind farm years). It is not surprising that availabilities increase because a "learning curve" effect is expected as equipment becomes better understood, and as routine maintenance and the corrective maintenance actions of repairs and replacements are executed in improved and more efficient ways.

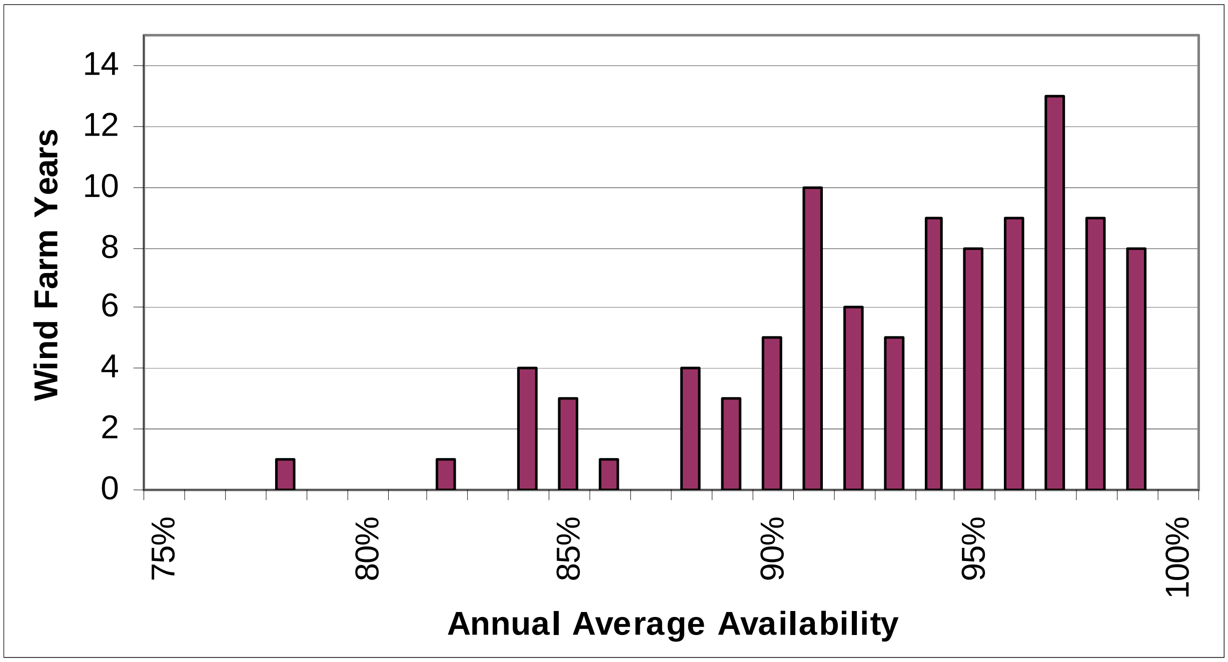


Figure 2. The Availability of a Wind Farm Goes Up With Years in Operation as Operators Understand the System and Can Increase Efficiency in Repairs and Replacements.

Reliability assessments interface with all aspects of design, as well as O&M requirements and limitations, and life cycle costs.

Section 3 - The Costs of Operations and Maintenance (O&M)

The costs of operations encompass expenses that are largely fixed from year to year and include things such as royalties for land use, taxes, insurance, personnel training, and other costs that may increase annually with inflation. Preventative maintenance costs are another such item. Other O&M costs are more variable. Corrective maintenance costs are driven by the failure of systems and components. Total O&M costs tend to increase with age in wind turbines just as they do in the maintenance of power plants, automobiles, and other types of infrastructures as the cumulative effects of age-related degradation take hold.

In the ***Wind Turbine Reliability: Understanding and Minimizing Wind Turbine Operation and Maintenance Costs,*** SAND 2006-1100[1] estimates of operating costs have been made through a number of studies for wind turbines. The annual O&M cost is indicated in $/kWh as the plant age ranges from the first year of operation through year 20 as shown in Figure 3.

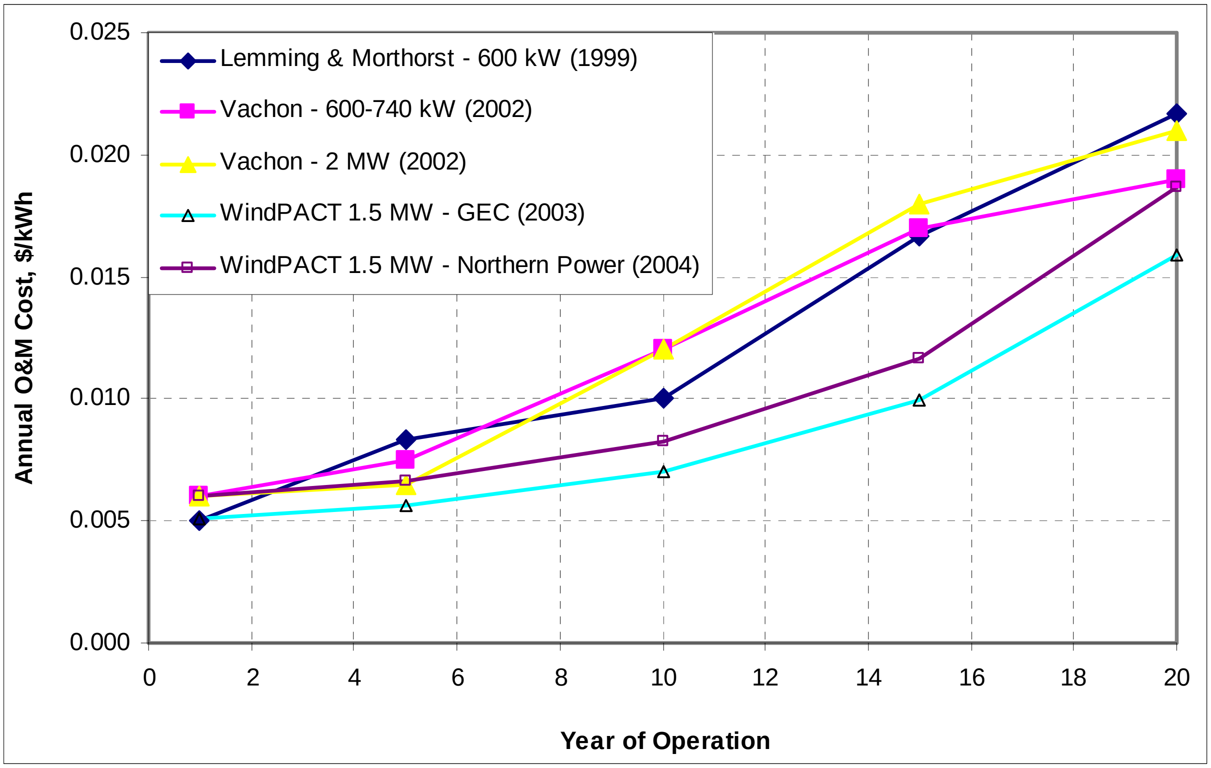
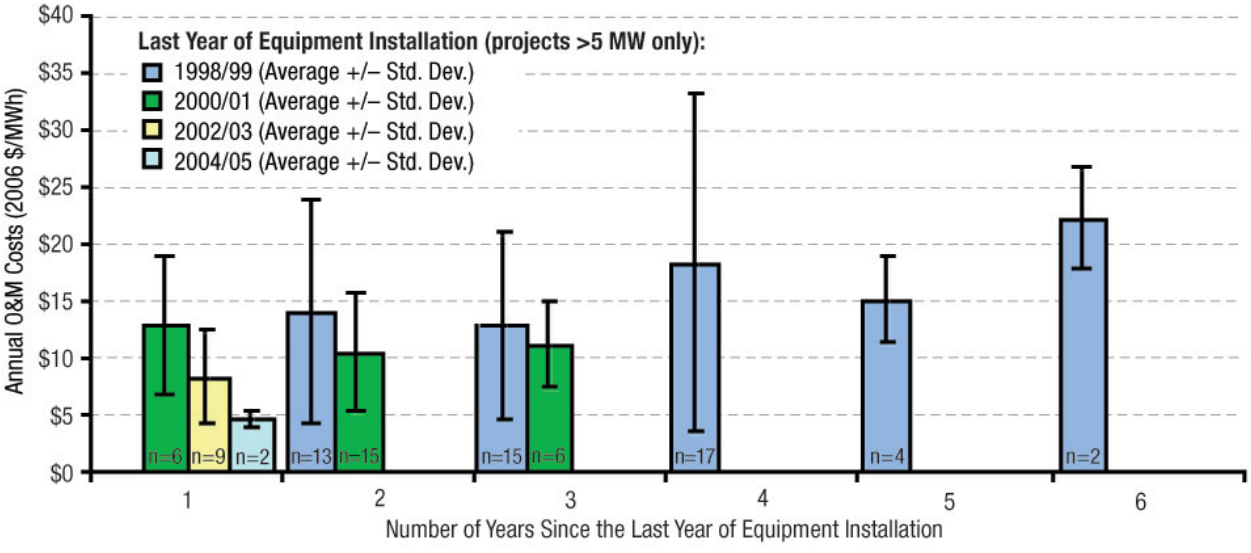


Figure 3. Total Operations and Maintenance Costs Increase with Age Due to Wear-Out Related Failures.

A more recent survey has been undertaken in the Annual Report on U.S. Wind Power Installation, Cost, and Performance Trends: 2006[3]. In this document, a survey of dozens of operating wind plants of recent construction has listing of O&M costs also expressed in terms of $/kWh by project age and last year of installation. See figure 4.



Source: Berkeley Lab database; averages shown only for groups of two or more projects.

Figure 4. Annual Average Operations and Maintenance Costs by Project Age.

For plants installed in the 1998/1999 time frames it is evident that O&M costs have tended to increase as time goes by, even approaching $.02/kWh estimates of the previous chart. It is interesting that the US Wind production tax credit (PTC) market incentive is currently $.019/kWh. O&M costs in the first 4 to 6 years are approaching this amount and out year expenditures remain to be determined. A present value case analysis of this cash flow demonstrates that the O&M costs are in fact of greater magnitude than the benefit of the PTC. Newer plants do not show such a distinctive trend although they typically are a level around $0.01/kWh.   The key to managing O&M costs may be in the reliability analysis of failures and corrective management practices.

Corrective maintenance costs stem from equipment failures, and while they may seem variable they can be statistically characterized through data gathered from process and repair records. This is an argument for developing and implementing processes that store O&M related data and ensure it is readily available for use in advanced maintenance practices. As one operator stated about the importance of data in operations and maintenance cost analysis “Tracking, tracking, tracking!”

The tracking of failures and associated costs of repair or replacement allow for reliability analysis techniques. This provides the basis for determining failure rates in terms of MTBF, MTTR, and Availability. Failures that require significant expenditures are readily revealed using Pareto analyses, another reliability technique that is also know as the law of the vital few, focuses attention on the contributors to the causes that contribute most to the effects. In short, Pareto analysis usually shows that 80% of the problems (cost, downtime, etc.) are caused by 20% of the causes. Pareto techniques can be used in the definition of maintenance strategies:

The consequences of all failures are not equal. Failure behavior and repair actions will determine costs.

In a paper by Rademakers[4], four maintenance categories are defined.

- Replacement of rotors, nacelles, gearboxes, and generators with external cranes
- Replacement of large components with internal crane
- Replacement of small parts
- Inspection and repair

Analysis of reliability assessments and looking to see where costs can be minimized, the following objectives were identified as part of an Optimization of O&M strategy

- Improvement of deployment of crew (maintenance strategy)
- Reduction of failure rates
- Fault tolerant operations
- Improvement of accessibility

Individualized tracking of wind turbine component failure rates are not yet readily available as public knowledge. However, as a part of the work presented in this paper, a greater understanding of components is expected

Section 4 - Failure Characteristics

The Institute of Electrical and Electronics Engineers (IEEE) Gold Book[5] addresses the fundamentals of reliability analysis as it applies to the planning and designs of industrial and commercial electric power distribution systems, including basic concepts of reliability analysis by probability methods, fundamentals of power system reliability evaluation, economic evaluation of reliability, cost of power outage data, equipment reliability data, and examples of reliability analysis. Preventive maintenance, and evaluating and improving reliability of the existing plant are also addressed. Chapter 10 provides a summary of equipment reliability data. Wind turbine components are not addressed except for common electrical power components such as cables, terminations, switchgear, transformers, etc...

It states "knowledge of the reliability of electrical equipment is an important consideration in the design and operation of industrial and commercial power distribution systems. The failure characteristics of individual pieces of electrical equipment, (i.e. components) can be partially described by the following basic reliability statistics:

a) Failure rate, often expressed as failures per year per component (failures per unit year):
b) Downtime to repair or replace a component after it has failed in service, expressed in hours (or minutes) per failure"

It further states, "For a system such as an electrical power facility, availability is a key measure of performance. An electrical power facility must operate for very long periods of time, providing power to other systems that perform critical functions. Even with the best technology and the most robust design, it is economically impractical, if not technically impossible, to design power facilities that never fail over weeks or months of operation."

The IEEE Gold Book includes tables of *Inherent Availability and Reliability Data*. In these tables are listed items such as

- Component
- Unit-years
- Failures
- Failure rate (failures/year)
- MTBF
- MTTR

Another source for reliability information is the renowned reliability expert Paul Barringer, P.E.[6] who has developed a Weibull Reliability Database for Failure Data for Various Components, available on his websites as a service to reliability engineers. This database lists components that are also found in wind turbines including roller bearings, gears, lubrications pumps, couplings, gaskets, circuit breakers, AC motors, and synthetic lubrications oils that all have typical Weibull Characteristic life in the 50,000 to 100,000 hours. If converted to years these components would experience lifetimes in the range of 6 to 12 years. Considerable engineering judgment should be employed when using these numbers for analysis. It should also be noted that the environment in which wind turbines operates is much more severe than typical plant applications. The development of a similar database for wind turbine components will be described later in this report.

The relationship between typical utility availability measures for traditional generation sources and the availability of a variable resource are different. For utilities and systems where the performance is expected to be continuous or on-demand, considerations of availability, and the consequences of non-availability, are different than that for wind turbine systems. For a variable resource such as wind, the emphasis is on maximizing output when wind is available, and performing as much as is possible of the maintenance during periods of slight wind.

Until such a wind turbine National Reliability Database (NRD) can be populated with sufficient data to form a statistically significant basis, estimates based on professional judgment values for failures rates are being implemented. Global Energy Concepts[7] has developed a table of over 40 wind turbine components included in an operations and maintenance cost model developed early in 2007. The table identifies parts, characterizes failures rates as either constant or as a Weibull function, and estimates repair/replacement costs with labor resources needed. Sandia has refined these values through an interactive process that was described in the introduction (site visits, O&M investigations, and telephone communications) and adjusted these values for input into our baseline reliability models.

One final note about failure rates: The requirements, needs, and expectations operators have in wind turbines O&M have mixed pedigrees. The power purchases generally are dominated by the resource (which is uncertain) with a minor adjustment for assumed availability. The need is to maintain the high availability without consuming the profits in O&M costs. The NRD is being created to understand where components and systems failures occur and to understand their consequences so that reliability can be improved.

Section 5 - National Reliability Database

Development of the National Reliability Database (NRD) is underway. The functional description of the Sandia Wind National Reliability Database is to:

a. Create a warehouse of all wind turbine data pertaining to events, timelines, and environments
b. Establish links between event times, and environments
c. Establish rules for determining failure rates, failure causes, availabilities, and repair times from database queries
d. Determine failure rates, failure causes, availabilities, and repair times for wind turbine components
e. Perform rudimentary parameter fitting: e.g. Weibull parameter values, strengths of trends

The process to start utilizing and analyzing the data will take some time, although many of the component reliability issues are already know. A process of recruiting data partners has begun and a *Reliability Data Collection, Analysis, and Reporting Plan* (Data Plan) has been written is included in Appendix B. The data may be electronic such as Supervisory Control and Data Acquisition (SCADA) systems, other process control management data historians, such as Plant Information (PI) systems, and automated maintenance systems. In many cases, data is not electronically available. For example, work orders and purchase orders for parts and crane services may be manually produced. Interviews with operators, consultation with asset managers' analysts and operators' reliability engineers has been and will be indispensable.

The NRD for wind turbines consists of data from multiple wind farms – see Figure 5. The data is uploaded to a central server at Sandia National Labs where it is normalized to a common definition of a wind turbine and a common definition of a failure event wherever possible. During the normalization process the individual links to specific wind farms are maintained for specific wind farm analysis and reporting but are kept anonymous for industry wide analysis and reporting. Currently the database has been designed based on SCADA data and maintenance reports and will be modified for multiple inputs from multiple data partners

The potential amount of information collected could be vast, and the expectations for the database will depend on the focus of the analysis required. Data is needed for many different purposes at many differing periods throughout the plant life. Initially, data needs include:

- Repair times including parts ordering time, travel and staging time, staff requirements, and equipment availability
- Mean times to failure for each turbine component
- Control system faults, time of occurrence, duration, component repair/replacement dates
- Environmental parameters
- Design configurations
- Power/loads
- Performance data

- Condition monitoring
- Scheduled maintenance times
- Repair times

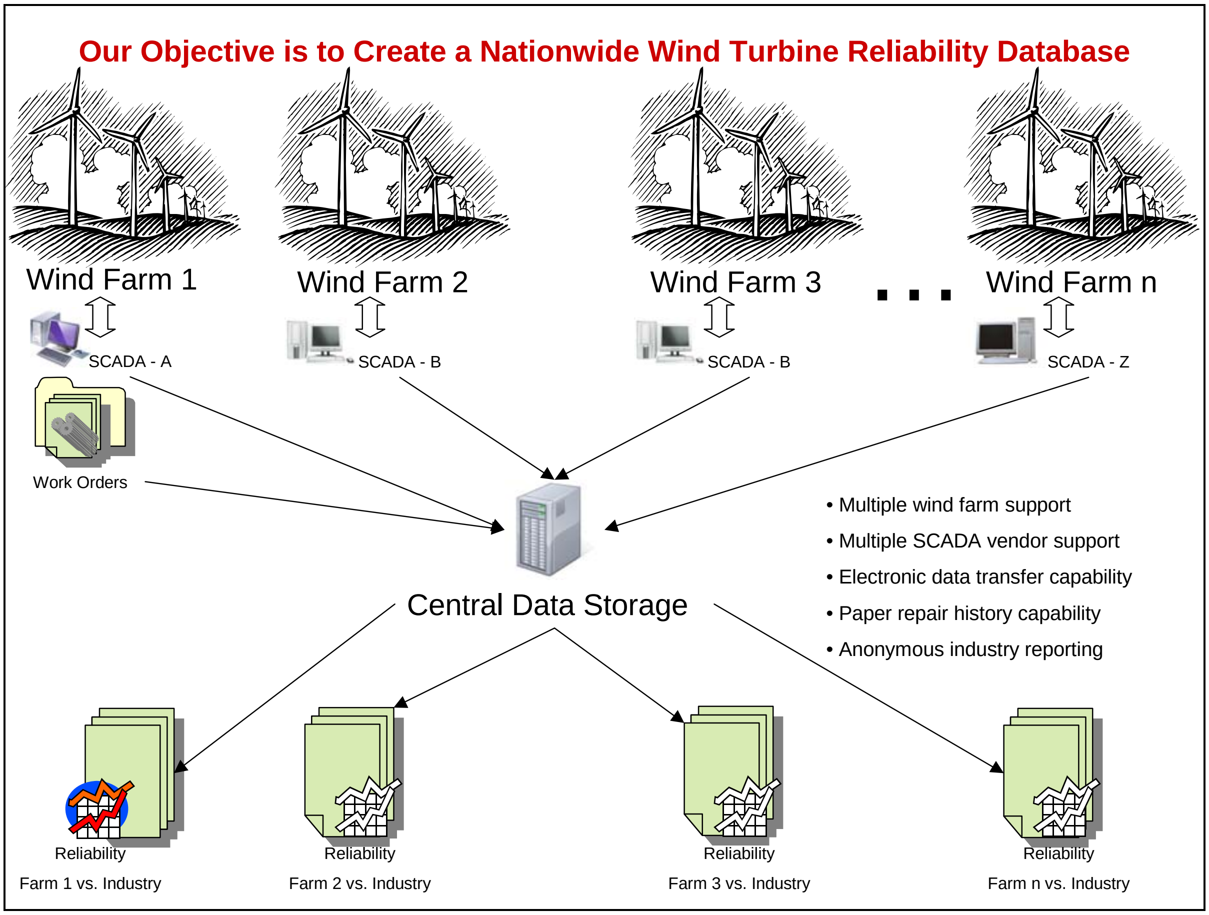


Figure 5. The Structure of the National Reliability Database for Wind Energy

The success of the database depends on the collection of statistically significant amounts of information and processing that data so that it can be used for reliability analyses and aggregation of individual inputs into industry baseline reports. Through efforts with the American Wind Energy Association (AWEA) O&M Working Group and others, this process has started. Figure 6 has been presented at meetings of this Group and it illustrates both the types of information for data collection, the database and analysis role of Sandia and the feedback loop of providing back synthesized information to the industry. It is acknowledged that failure information is sensitive and throughout this process no individual wind plant, turbine manufacturer, or subcomponent vendor will have its reliability information released. This whole process is still in the initial stage and the database will be used for broad reliability analyses that are expected to identify technology improvement opportunities that could spawn future individual component improvement activities.

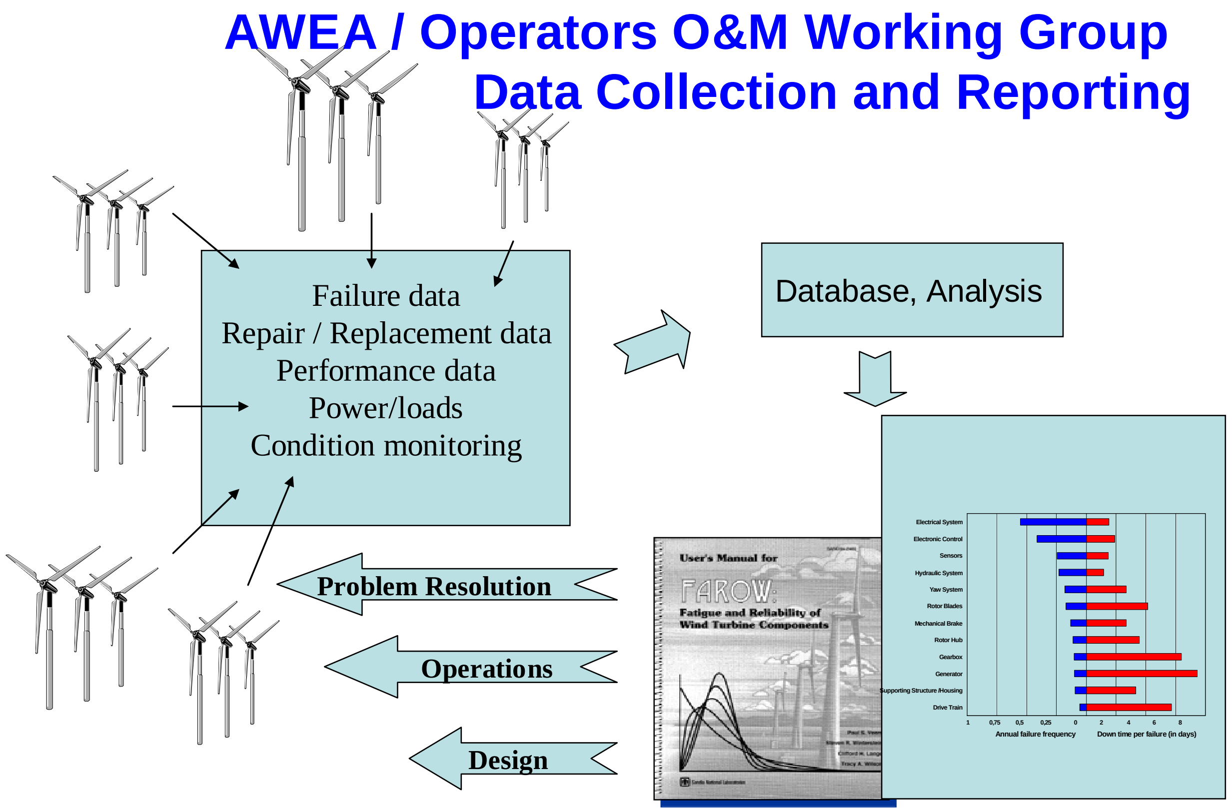


Figure 6. AWEA O&M Working Group Data Collection and Reporting

This illustration shows the partnerships necessary for data collection and reporting. Industry interactions are addressed later in this report. Consistent feedback from industry data partners is a fundamental and necessary component for this system.

Section 6 - Reliability Modeling

Reliability modeling is a process used to understand the complexities of a system and determine how component failures affect the operation of the larger system. The modeling process divides the system into discrete components, organizing them in a manner that simulates their physical function, and uses empirical data to derive statistical distributions that estimate failure rates to predict performance of the system.

Reliability modeling is a long-term activity involving the creation of a system taxonomy, which includes breaking the system down into its respective parts and failure modes, acquisition of information (population of the database), refinement of the reliability model, and improving system design. This process:

- Improves understanding of the system
- Allows for early evaluation of design alternatives
- Identifies critical component failure modes and failure interactions
- Guides resource allocations to parts of the system needing improvement
- Enhances the interface between design and operations.

There are two modeling techniques currently used at SNL for wind farm reliability modeling – reliability block diagram (RBD) modeling and fault tree analysis. The software used for RBD is a commercially available package called Raptor. For the fault tree analysis, an internally developed software package called Pro-Opta is used. RBDs and fault trees are similar in that they break down the system into a logical structure. Raptor provides a simulation model of the system and Pro-Opta can import field data. Their use is complementary.

6.1 Raptor Modeling

A large wind farm operates as a fleet of turbines in a modular approach, where each turbine operates largely independent from the other (in parallel), as shown in figure 7. The turbines in this field operate largely independently of each other and illustrate “modular” operating characteristics. Each turbine is composed of components that work in series, meaning that for the turbine to work, all components must be functioning. Each of the turbines in Figure 7 can be “drilled down” to show individual components, as demonstrated in Figure 8. Each of these component blocks has multiple inputs that allow for modeling of preventative and corrective maintenance, human resource requirements, operational dependencies, costs of operations and repair, and other logistical assessments, as shown in Table 1.

The first important objective when modeling a system is to facilitate an understanding of how the reliability of wind turbine components impacts the overall wind farm system availability and resultant energy production. From that baseline information, “weak link” analyses can be performed for the system to determine which components contribute most to cost, downtime, and availability. From this, the modeling software can be used to perform scenario analysis, where the effects of the weak link components can be analyzed by increasing or degrading mean times between failures, repair times, costs, and other component inputs.

Raptor is designed for scenario modeling, which allows the user to model different operating scenarios and determine their effect on the overall performance of the individual turbine and the entire wind farm. For example, the installation of climb assist systems can be modeled, and the impacts on cost, availability, and reliability can be ascertained. The effect of maintenance strategies, including sparing strategies, capital expenditures, and other potential operational scenarios can be modeled virtually and the results analyzed in the matter of a few minutes on the computer. In this way, designs that can improve reliability or mitigate repairs and replacements can be considered. Big items already known to have significant repair costs are those that require cranes for service. Blades, generators, and gearboxes typically fall into this category. The effects of changing the approach to blade control, the type of gearboxes, the possibility of permanent magnet generators and redundancy can be modeled. Other aspects such as integrated lifting devices, selection of electrical vs. mechanical systems for increased reliability, or increased maintainability and availability, or general minimization of costs can also be examined

Turbines need periodic preventative maintenance as well as corrective maintenance. Consumable supplies will be based on regular maintenance requirements. Again, the modeling is based on frequency of failures and time distance, hauling and crew requirements, and understanding of the logistical needs. Such factors will be included in the mean time to repair calculations, and combined with failure frequencies, this will determine plant availability. Corrective maintenance will consist of specific repair or replacement of failed components. Accessibility is an input to availability.

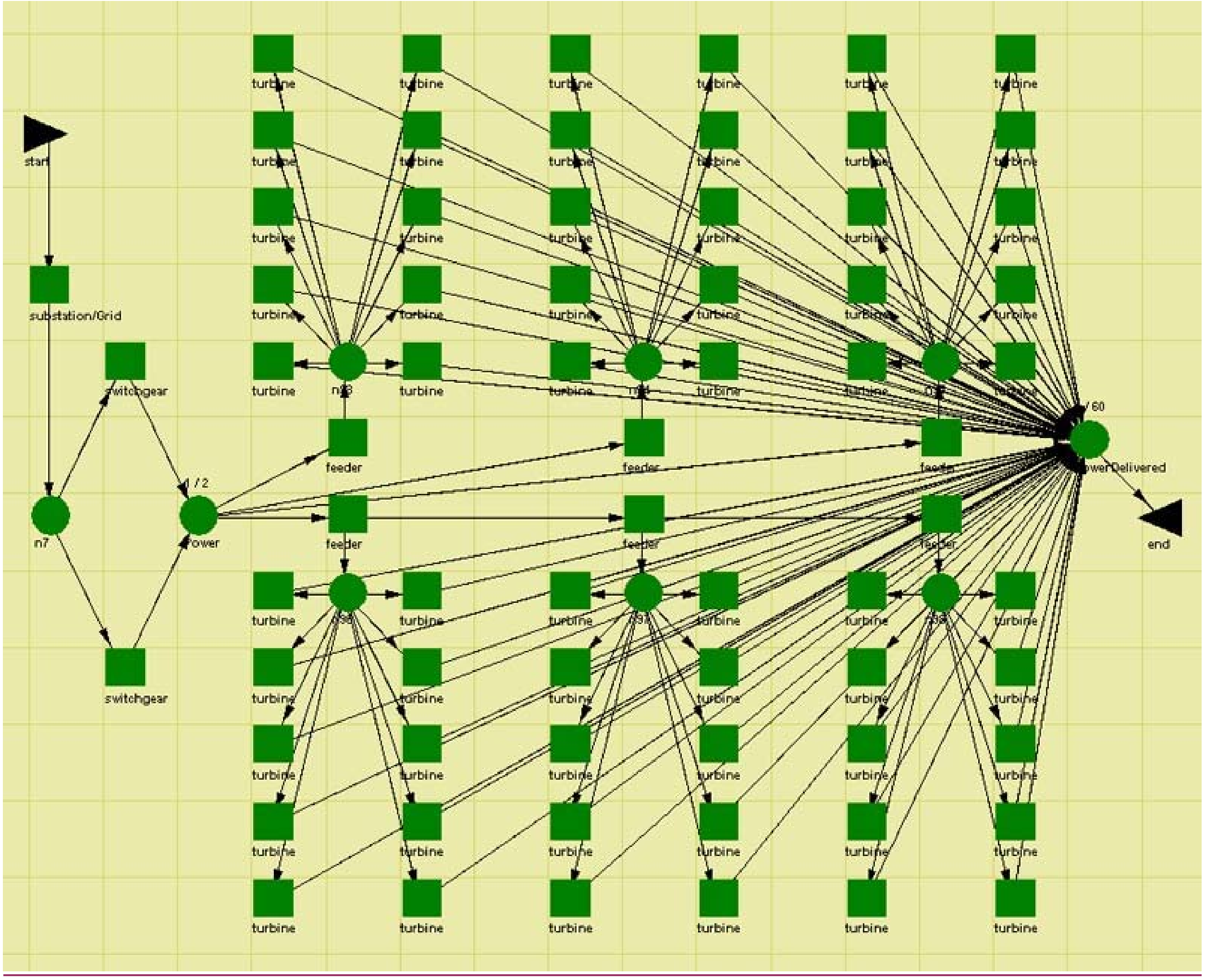


Figure 7. Reliability Block Diagram of Multi-Turbine Wind Farm.

The ability exists to drill down into each of the turbines represented above, allowing the user to model turbines at the component level for understanding of impacts, as shown in Figure 8.

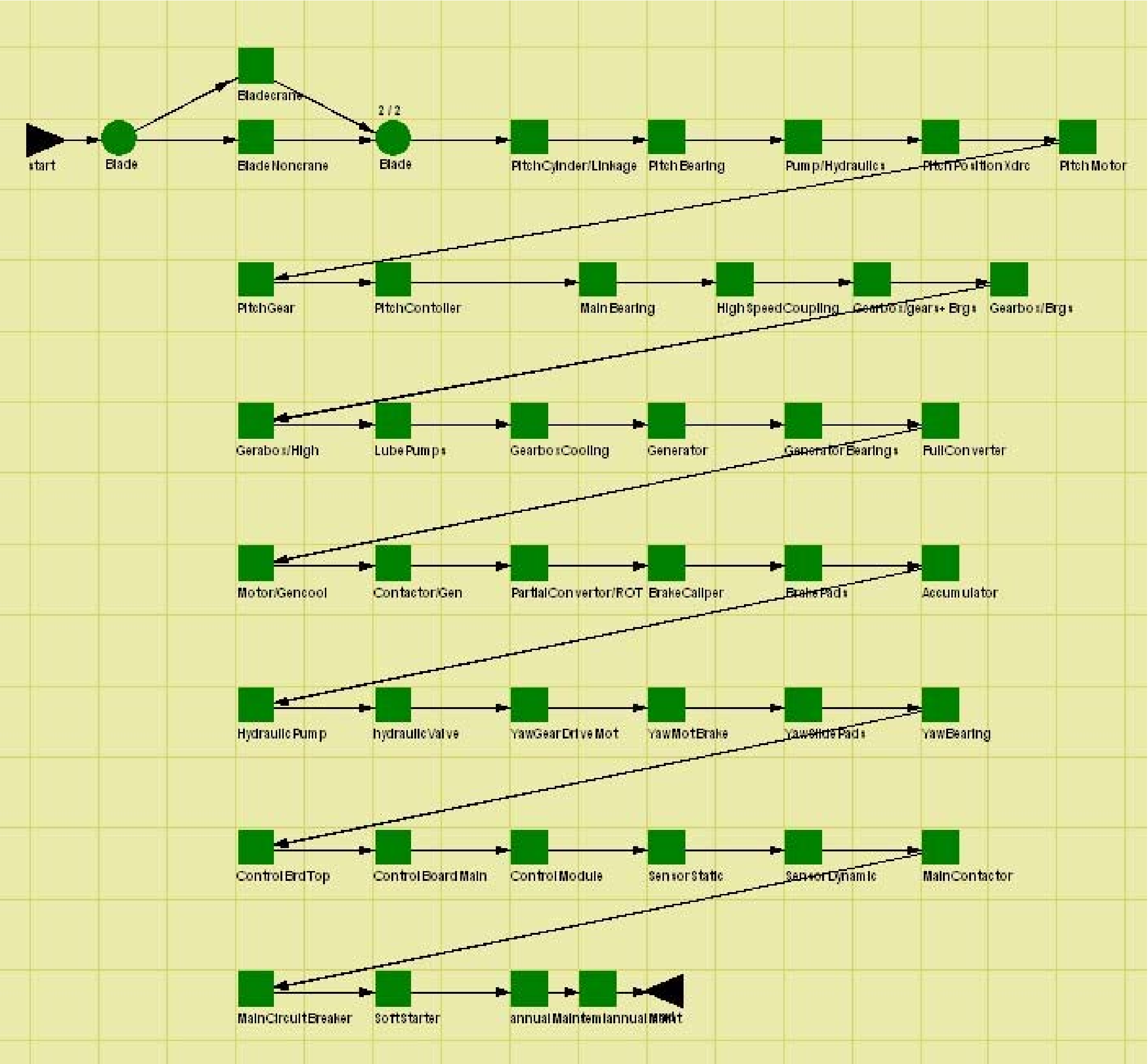
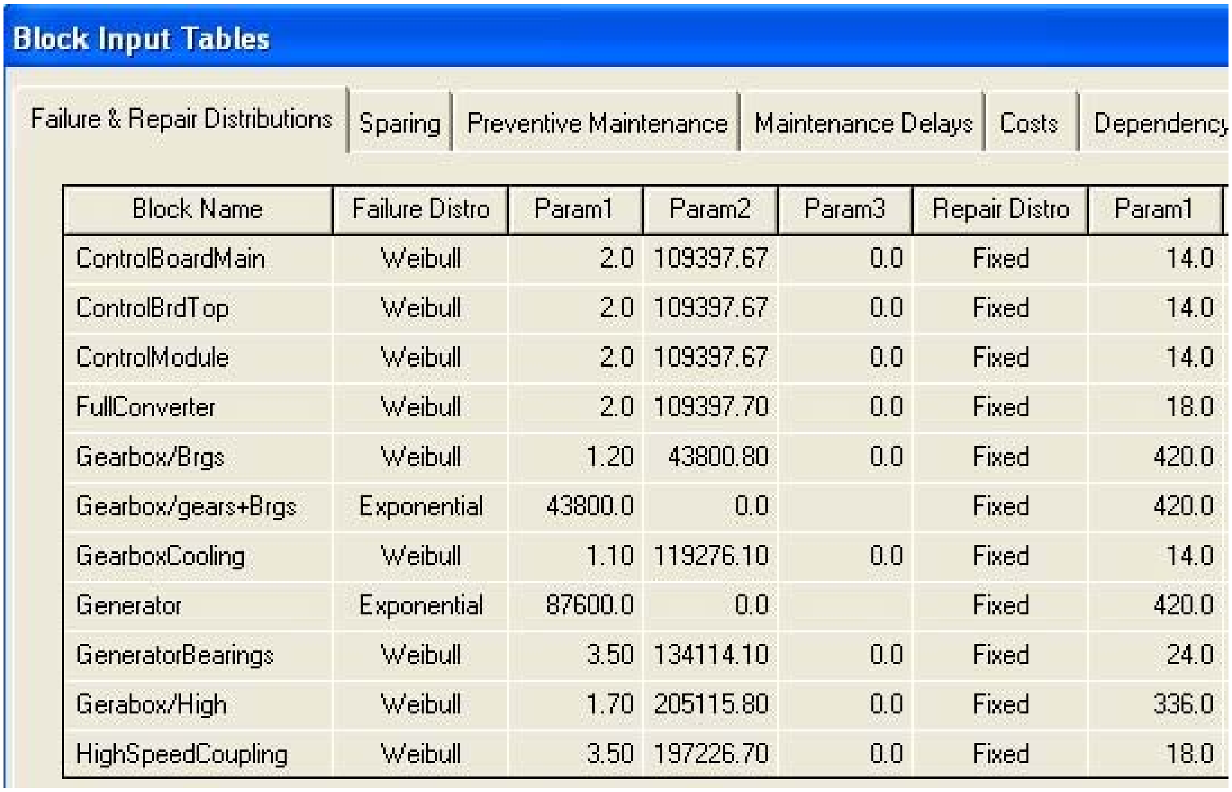


Figure 8. Drill Down of a Wind Turbine and Shows the Component Hierarchy of a Single Wind Turbine.

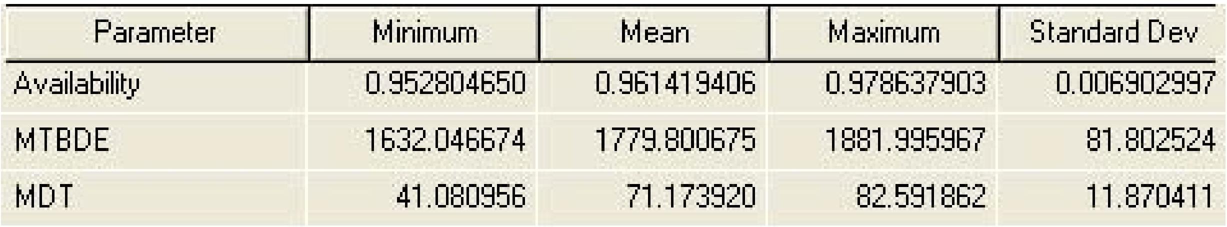


Block Name	Failure Distro	Param1	Param2	Param3	Repair Distro	Param1
ControlBoardMain	Weibull	2.0	109397.67	0.0	Fixed	14.0
ControlBrdTop	Weibull	2.0	109397.67	0.0	Fixed	14.0
ControlModule	Weibull	2.0	109397.67	0.0	Fixed	14.0
FullConverter	Weibull	2.0	109397.70	0.0	Fixed	18.0
Gearbox/Brgs	Weibull	1.20	43800.80	0.0	Fixed	420.0
Gearbox/gears+Brgs	Exponential	43800.0	0.0		Fixed	420.0
GearboxCooling	Weibull	1.10	119276.10	0.0	Fixed	14.0
Generator	Exponential	87600.0	0.0		Fixed	420.0
GeneratorBearings	Weibull	3.50	134114.10	0.0	Fixed	24.0
Gerabox/High	Weibull	1.70	205115.80	0.0	Fixed	336.0
HighSpeedCoupling	Weibull	3.50	197226.70	0.0	Fixed	18.0

Table 1. Failure Rate Information, repair or replacement times periods, resource requirements, dependencies, logistical constraints, parts inventories all form part of the inputs into the wind turbine components shown in Figure 8.

6.2 Raptor Modeling Results

Various raptor outputs are available. As demonstrated in Table 2, the min, max, and mean availability can be shown, along with the mean time between downing events (essentially, mean time between failures) and mean down time. In addition, the user can specify other outputs in table format, including reliability, cost, and capacity.



Parameter	Minimum	Mean	Maximum	Standard Dev
Availability	0.952804650	0.961419406	0.978637903	0.006902997
MTBDE	1632.046674	1779.800675	1881.995967	81.802524
MDT	41.080956	71.173920	82.591862	11.870411

Table 2. Raptor Results showing max, min and mean values for availability, mean time between downing events, and mean down time.

Raptor can also display results graphically, as shown in Figure 9 – a “weak link” analysis where different colors for each block represent availability thresholds determined by the user – red being unacceptable, yellow being “needs work,” and green being acceptable.

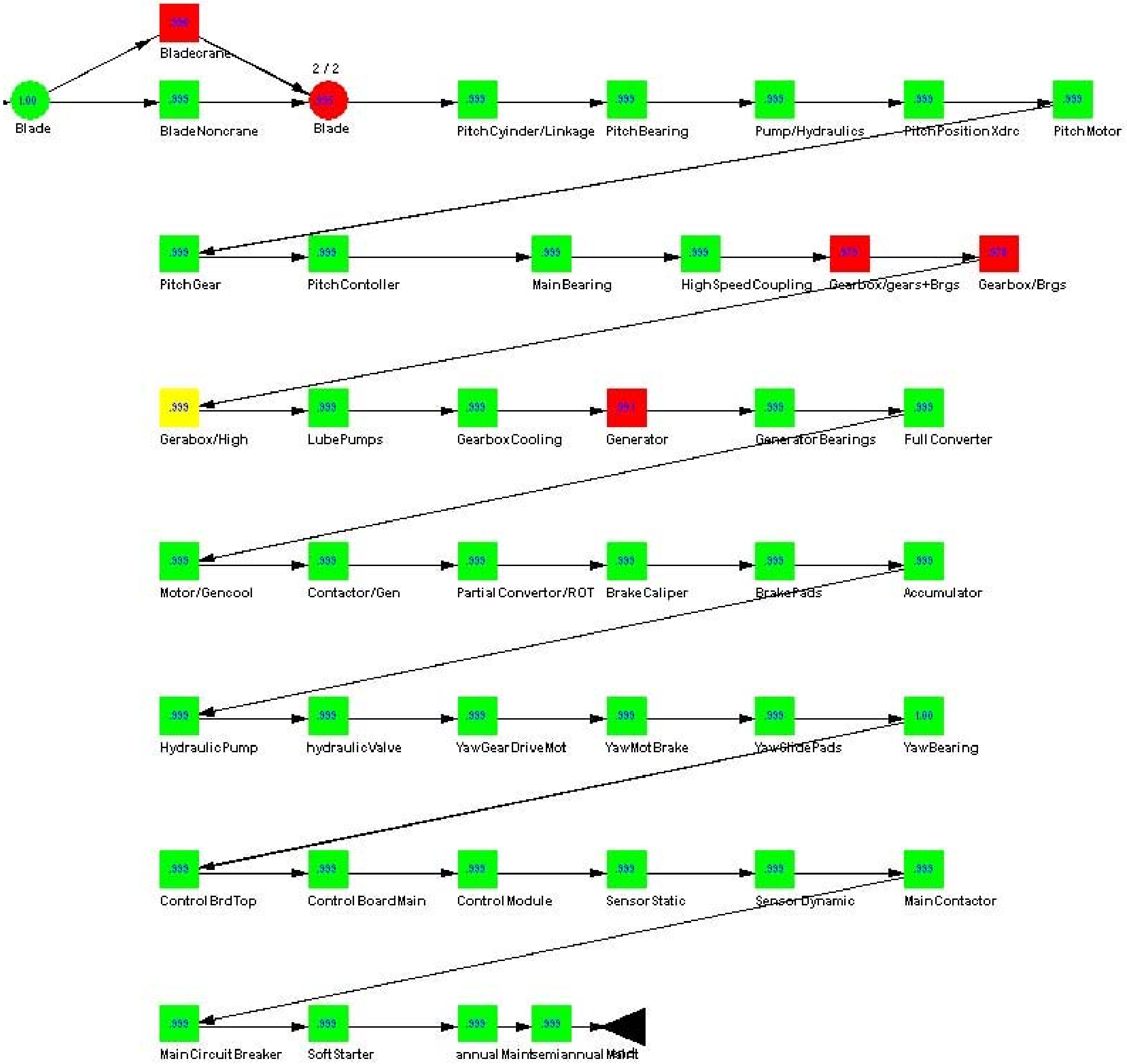


Figure 9. Raptor Graphical Results representing “weak links” in the system, where red represents an unacceptable level availability.

6.3 Static Fault Tree Analysis Modeling Using Pro-Opta

Another tool being used to evaluate wind farm reliabilty and availability is Pro-Opta. The Pro-Opta software package is a reliability analysis and optimization program developed by Sandia National Laboratories. Pro-Opta is intended to provide current system reliability performance and cost-benefit decision analysis using current system relaibility performance and alternative improvement options. Its decade of use includes analysis of the Army's Apache helicopter, the Navy's Landing Craft, Air Cushioned (LCAC), the Airborne Laser (ABL), and the Shadow Unmanned Aerial Vehicle (UAV). Figure XX shows the primary modules of the Pro-opta Toolset and the following paragraphs describe the purpose of each of those modules

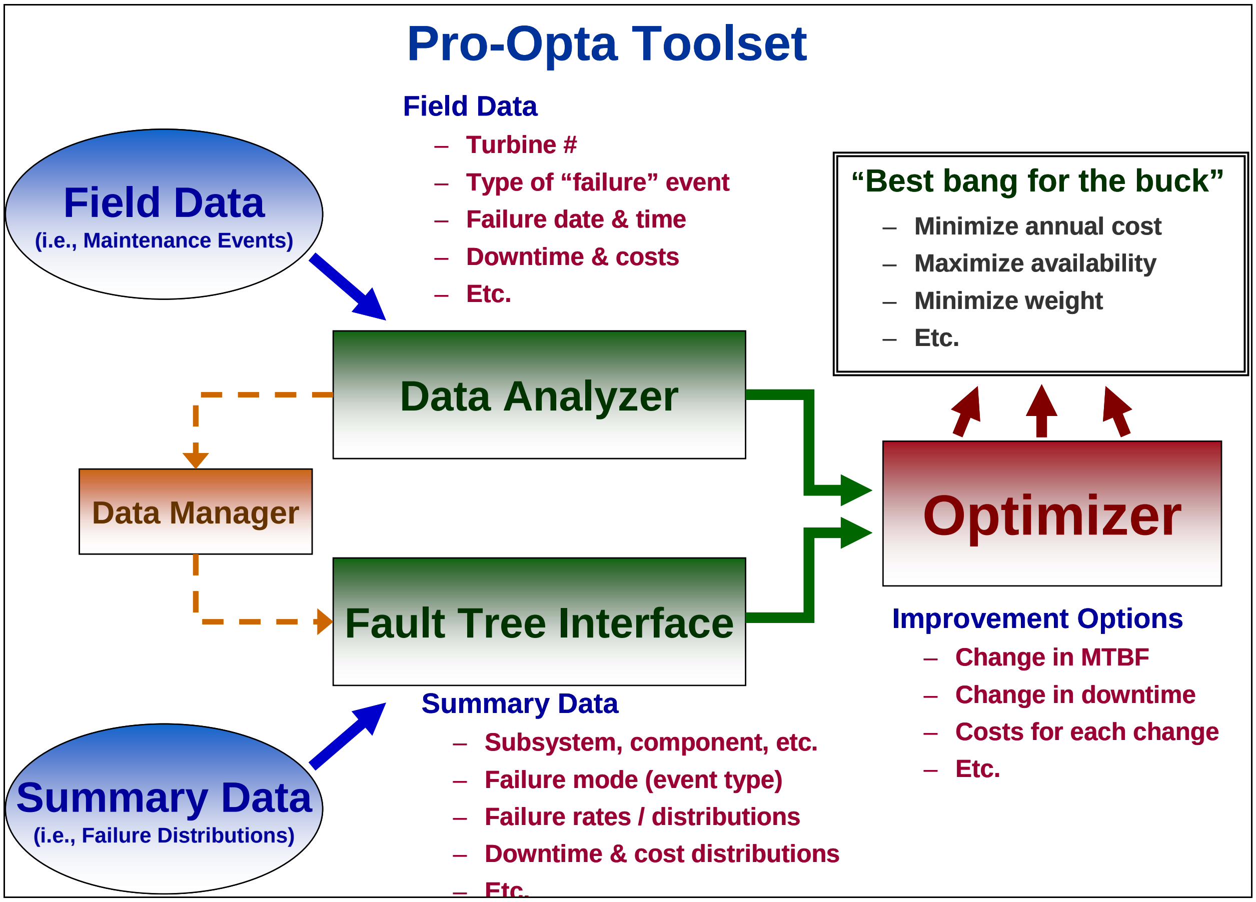


Figure 10. Pro-Opta Toolset

Pro-Opta's Data Analyzer imports field data and analyzes the data as a serial fault tree. The field data must contain records of the "failure events" (component failures, inspections, scheduled maintenance, etc.) that have occurred on each system (individual wind turbine, aicraft, truck, ship, etc.). The type of field data necessary to evaluate a system's reliability, availability, and maintainability includes, but is not necessarily limited to:

- System ID – Distinguishes individual system (i.e., wind turbine number)
- Failure event code – Identifier for type of failure event
- Failure event name – Descriptive text for types of failure events
- Failure date – Date when failure event occurred
- Failure time – Time of day when failure event occurred
- Total downtime – Total time equipment was non-operational
- Event type – Type of downtime (e.g., scheduled, unscheduled, inspection)
- Cost data – (e.g., component, man-hour, lost revenue)

The Data Analyzer uses this field maintenance event data in several ways. It determines which failure events are driving fleet (e.g., wind farm) level performance measures such as MTTR, MTBF, cost, and availability. Data Analyzer also reveals how each individual system (e.g., individual wind turbine) performs in terms of availability and what are the major causes of that individual system's downtime. The various performance measures' values can be viewd in either tabular form (summary statistics, raw data) or graphical form (histograms, cumulative distribution functions, Pareto charts). These results help focus the decision maker on the failure events that need to be improved upon in some fashion so that system availability can be increased and costs can be reduced. An optimization study can be built on a model generated by Data Analyzer.

The Data Manager is used for several reasons. First, if failure dates, failure times, and total downtimes are not known (or trusted) for any number of the field data failure modes identified in the field data, known or estimated failure rates, failure rate distributions, downtimes, and downtime distributions can be inserted into the baseline reliability model exported from the Data Analyzer. Second, failure modes and their associated failure rates, failure rate distributions, downtimes, and downtime distributions can be added to the baseline reliability model when the failure modes are not yet observed in the field maintenance data. Third, the Data Manager can be used to develop a completely new fault tree model of a system using known or anticipated failure modes and their known or estimated associated failure rates, failure rate distributions, downtimes, and downtime distributions. In each case, the resultant failure mode library can be used in the Fault Tree Interface to obtain current or projected system performance.

The Fault Tree Interface provides the capabilty to develop and examine series or nonseries fault trees for new designs or existing systems using the failure mode libraries exported from the Data Analyzer into the Data Manager, or created in the Data Manager. Cost information can be input and correlations among failure modes can be defined

The Fault Tree Interface 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 where the performance measures are examined in a statistical framework. The various performance measures' values can be viewd in either in tabular form (summary statistics, raw data) or graphical form (histograms, cumulative distribution functions, Pareto charts). Multiple fault trees, representing different configurations of the same system or distinctly different configurations that share some components can be analyzed at the same time. Like the Data Analyzer, an optimization study can be built on a model generated by the Fault Tree Interface.

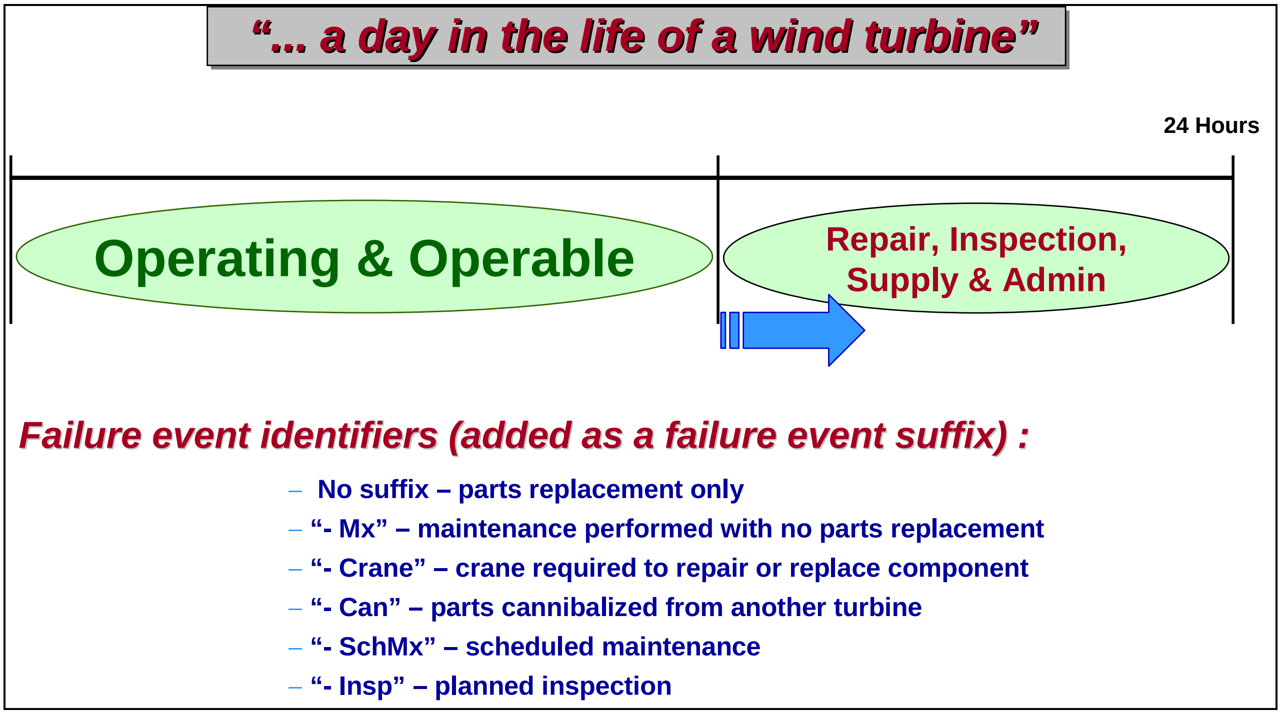
Pro-Opta's Optimizer is designed to perform system improvement and spare parts (components) optimizations. System improvement optimization determines the best set of component modifications and changes in maintenance practices that can increase availability and minimize cost within the reliability and cost constraints specified. Normally, the improvement options are supplied through engineering estimates, data modified from similar components, or limited test data. Spare parts optimization helps to determine the best set of spare parts to keep on hand within the downtime and cost constraints specified. For both types of optimizations, the Data Analyzer or Fault Tree Interface provide the system reliablity models that serve as the baseline or starting point for the optimization process. The type of data needed for system improvement and spares optimization analyses include:

- Failure rate improvements for each upgrade/modification of selected items
- Downtime improvements for each upgrade/modification of selected items
- Costs associated with each upgrade/modification ($$s, weight, volume)
- Expected parts obsolescence timelines and associated costs
- Downtimes with and without an on-site spare
- Spares restock time
- Expected spares availability and associated storage costs, if any

[It should be noted that in terms of spare restock time and spare availability, that there has (recently) been a bottleneck in the component supply chain. The supply situation is most constrained for rotor blades, gearboxes, large bearings for gearboxes and mainshafts, generators, and cast iron and forged items[8].]

Pro-Opta can also optimize over multiple fault trees (i.e., systems, configurations, etc.) that may or may not share common failure modes (i.e., components, inspections, etc.) so that the benefit of an improvement that affects multiple systems or configurations can be quantified.

For the wind turbine availability assessments, a systems approach is used to determine key availability drivers using Pro-Opta. Instead of modeling only component reliability, the approach will consider all available information that may affect "a day in the life of a wind turbine." The goal of the optimization is to minimize the time waiting on repairs, inspections, maintenance, and supply by identifying what is actually causing downtime. These downtime "drivers" may or may not be strictly component reliability issues. To do that, additional identifiers are added to the failure modes to help distinguish the cause of the associated downtime. Several of these additional identifiers are shown in Figure 11.



"… a day in the life of a wind turbine"

24 Hours

Operating & Operable

Repair, Inspection, Supply & Admin

Failure event identifiers (added as a failure event suffix) :

- No suffix – parts replacement only
- "- Mx" – maintenance performed with no parts replacement
- "- Crane" – crane required to repair or replace component
- "- Can" – parts cannibalized from another turbine
- "- SchMx" – scheduled maintenance
- "- Insp" – planned inspection

Figure 11. Additional Failure Mode Identifiers

Using the modified GEC data described in Section 4, model runs were made to demonstrate the capability of Pro-Opta to provide contributors to availability and cost (among many other types of results that include MTBF and MTTR). Figure 12 shows the top ten contributors to availability (actually non-availability) and the top ten contributors to cost for comparison. The Pareto in Figure 12 shows that the gearbox, generator, and rotor blade failure modes provide a much greater relative impact on the average availability of 93.88% than the remaining failure modes. The top ten failure modes for availability are the result of a combination of frequency of occurrence and length of downtime. Both the Annual Inspection and Semi-Annual Inspection appear in the top ten contributors to availability because they occur quite frequently despite having relatively short downtimes of eight and six hours, respectively.

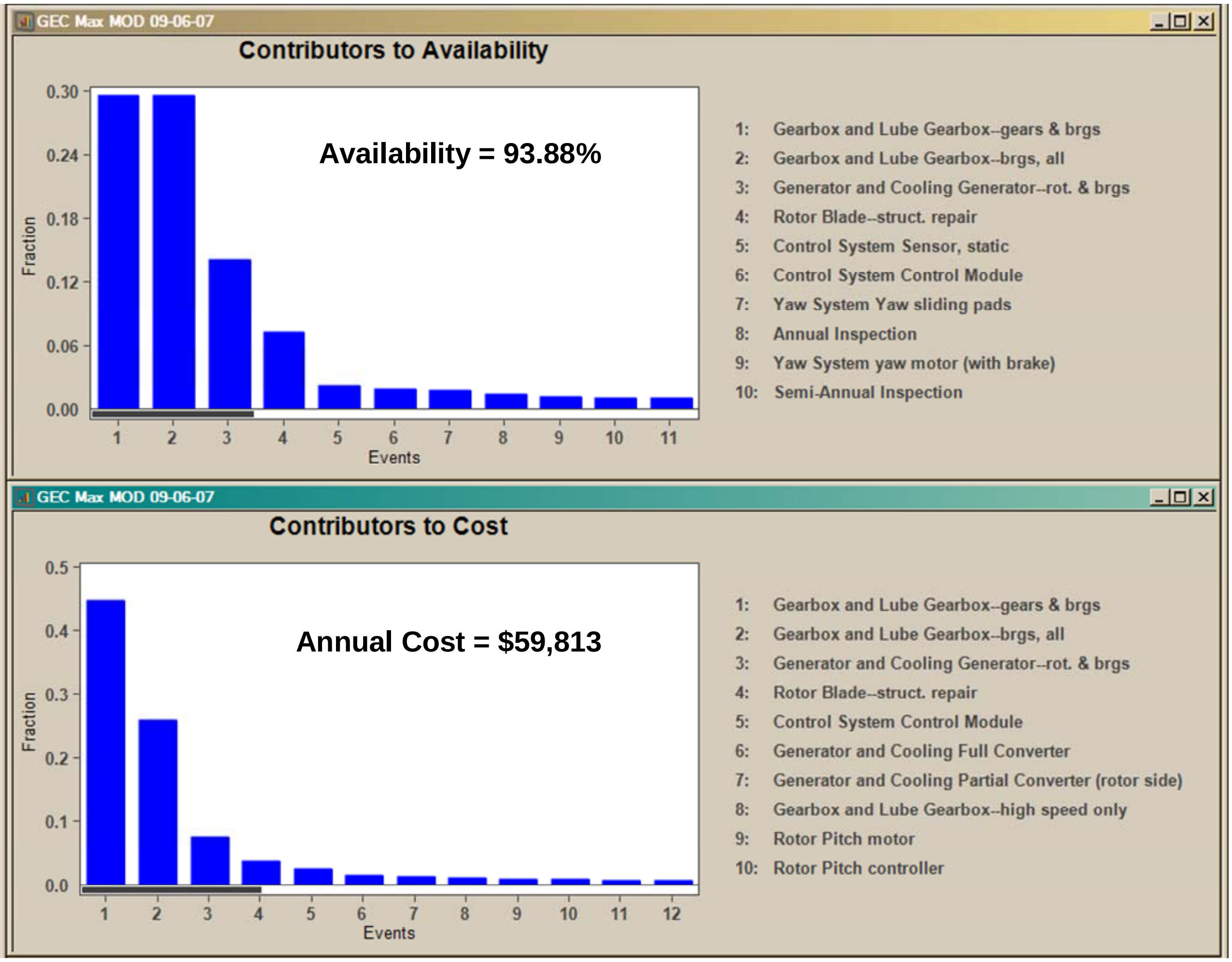


Figure 12. Top Contributors to Availability and Annual Cost

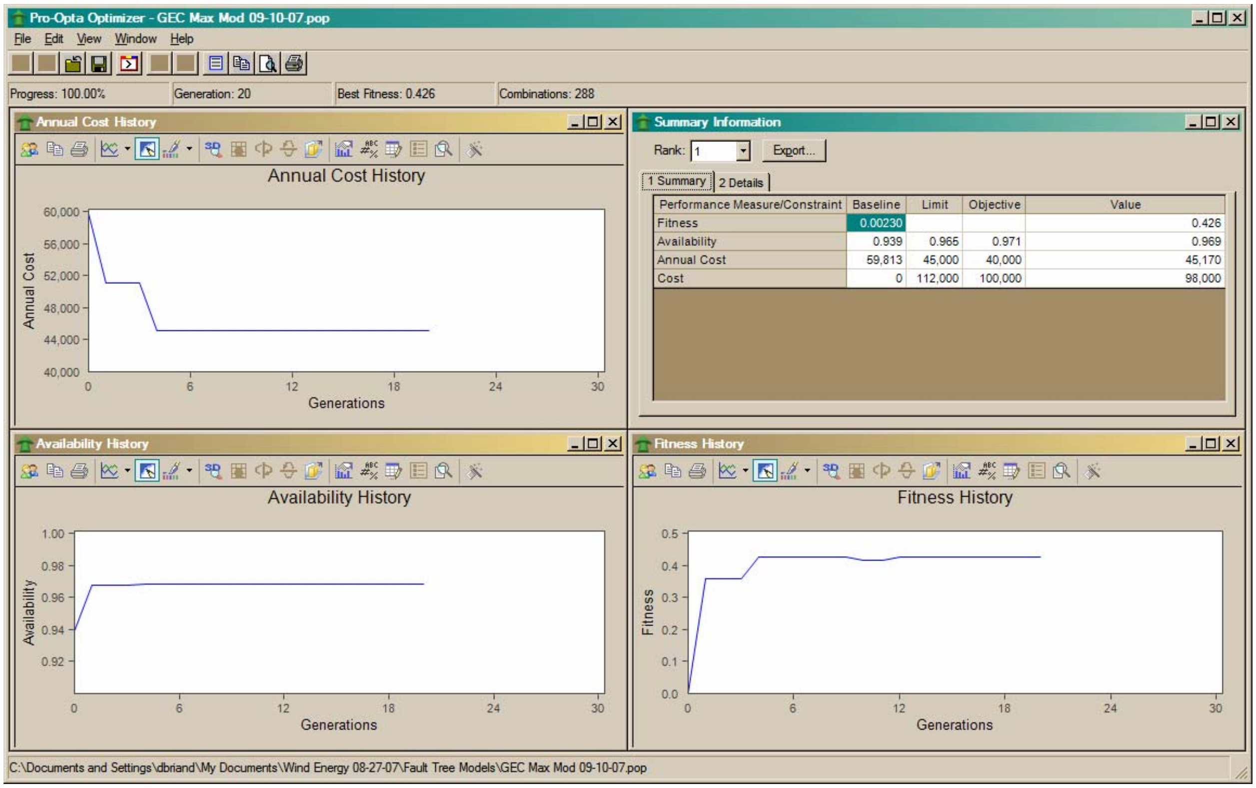
The top ten contributors to cost in Figure 12 show a similar result as the contributors to availability, although only the top three failure modes (gearbox and generator) provide the greatest impact on an average annual cost per turbine of $59,813. Here, the top ten failure modes for cost are the result of a combination of frequency of occurrence and component cost.

To demonstrate the capability of the Optimizer, purely illustrative improvement options and associated implementation costs were created as shown in Table 3. Each improvement option shows either a percent improvement in TTF and/or in downtime at a specified implementation cost. In this demonstration, the Gearbox – Overhaul Upgrade and the Blade Repair Modification had two levels of improvement, where the second level of improvement had additional cost. Where there are a significant number of improvement options, Pro-Opta provides a genetic algorithm that finds optimal or near optional solutions with much less computer run time.

Improvement Option Name	% TTF Improvement	% Downtime Improvement	Implementation Cost	Level
Gearbox -- Overhaul Upgrade	15	0	$20,000	1
Gearbox -- Overhaul Upgrade	30	0	$50,000	2
Gearbox -- PHM Implementation	0	50	$7,000	1
Generator Improvement	30	0	$10,000	1
Blade -- Specification Change	25	0	$15,000	1
Blade -- Repair Modification	5	5	$1,000	1
Blade -- Repair Modification	10	10	$5,000	2
Spares Inventory Increase	0	35	$30,000	1
Crane -- Long Term Rental	0	50	$46,600	1

Table 3. Illustrated Example of Improvement Options and Implementation Costs.

The optimization of the nine alternative improvement options uses the baseline system reliability model developed earlier with starting points for availability and annual cost of 93.88% and $59,813, respectively. The optimization process moves through possible combinations of improvement options seeking to achieve the limits and objectives set as part of the optimization setup. In this demonstration for example, the limit (the minimum level of improvement desired) and the objective (the actual level of improvement desired) are set at 96.5% and 97.1% availability, respectively, and $45,000 and $40,000 annual cost, respectively. The limit and objective on the total project cost (Cost) are set at $112,000 and $100,000, respectively. Figure 13 shows how the availability increases and the annual cost decreases as the generation of possible solutions progress within the limits and objectives set for Availability, Annual Cost, and Cost. The optimization uses the fitness function, which is based on the limits and objectives, to keep “moving” towards an optimal solution (there may be more than one). The final solution shows that for $98,000 in total project cost (POC), an increase in availability to 96.9% and a reduction in annual cost to $45,170 were achieved.



Progress: 100.00%

Generation: 20

Best Fitness: 0.426

Combinations: 288

Rank: 1

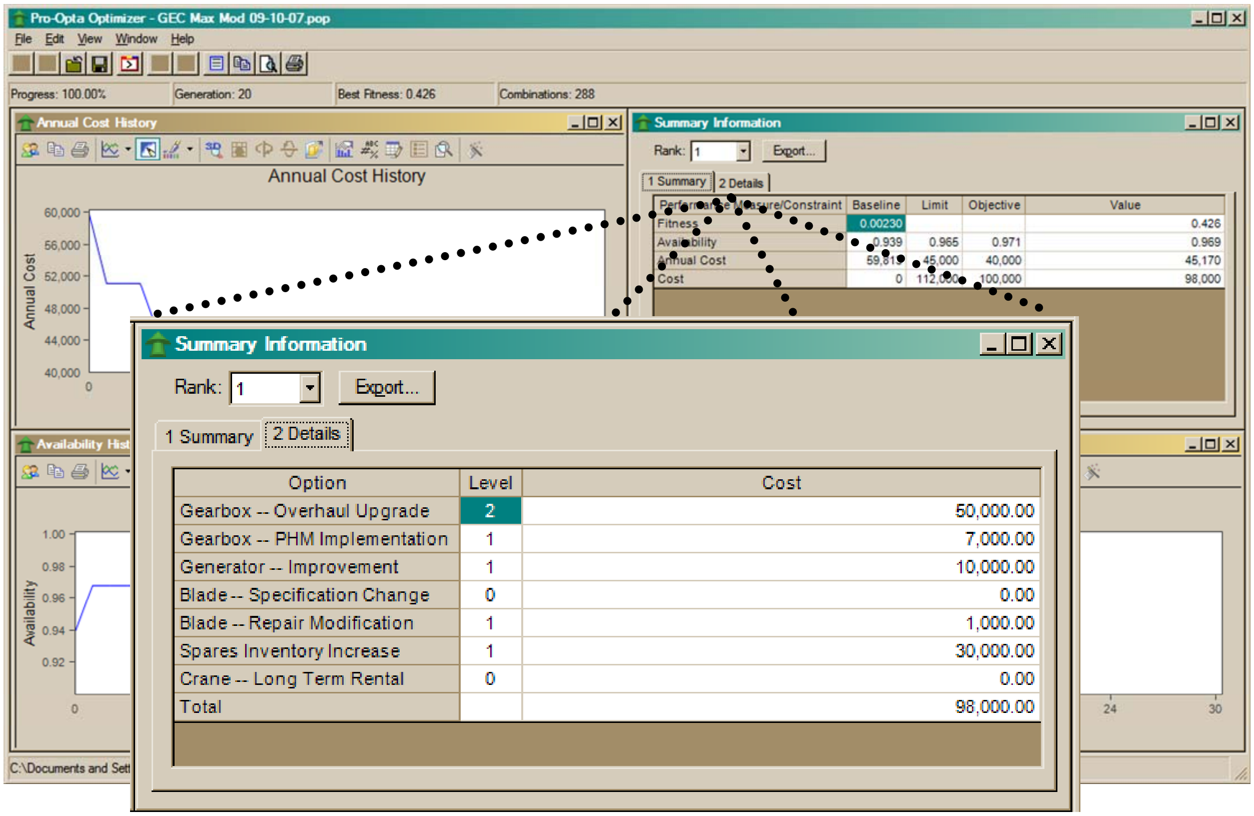
1 Summary | 2 Details

Performance Measure/Constraint	Baseline	Limit	Objective	Value
Fitness	0.00230			0.426
Availability	0.939	0.965	0.971	0.969
Annual Cost	59,813	45,000	40,000	45,170
Cost	0	112,000	100,000	98,000

C:\Documents and Settings\dbriand\My Documents\Wind Energy 08-27-07\Fault Tree Models\GEC Max Mod 09-10-07.pop

Figure 13. Illustrated Example of Optimization Results

The results of the optimization provide which improvement options should be pursued and where multiple levels of an improvement option occur, what level should be pursued. The total cost of the combinations of recommended improvement options is also provided. Figure 14 shows the recommended improvements for the notional example.



Progress: 100.00%
Generation: 20
Best Fitness: 0.426
Combinations: 288

Performance Measure/Constraint	Baseline	Limit	Objective	Value
Fitness	0.00230			0.426
Availability	0.939	0.965	0.971	0.969
Annual Cost	59,819	45,000	40,000	45,170
Cost	0	112,000	100,000	98,000

Option	Level	Cost
Gearbox -- Overhaul Upgrade	2	50,000.00
Gearbox -- PHM Implementation	1	7,000.00
Generator -- Improvement	1	10,000.00
Blade -- Specification Change	0	0.00
Blade -- Repair Modification	1	1,000.00
Spares Inventory Increase	1	30,000.00
Crane -- Long Term Rental	0	0.00
Total		98,000.00

Figure 14. Illustrated Example of Optimization Results

Pro-Opta has the capability to simultaneously analyze individual wind turbines or groups of wind turbines. It can be used to transform field data into a series and/or parallel fault tree with failure rates, failure rate distributions, downtimes, and downtime distributions which can be updated, amended, or corrected depending upon the quality of the field data, availability of summary data, and the type of reliability analysis. Multiple wind turbine fault trees can be analyzed and optimized simultaneously, a feature particularly applicable to wind farms with more than one type of wind turbine. The optimization capability can provide immediate insight into “what-if” scenarios based on the current performance of a particular wind turbine or wind farm.

Section 7 - Industry Interactions

The Sandia National Laboratories' Wind Reliability program interacts with many industry groups, including non-profits such as the American Wind Energy Association (AWEA), the Utilities Wind Integration Group (UWIG), and others including Original Equipment Manufactories (OEMs) and sub component manufacturers; service and support firms including consultants, turbine repair specialists; wind farm developers; and owners and operators.

> AWEA and UWIG are interested in exchanging information and have both formed O&M working groups. These groups share experiences and explore issues related to wind turbine operation and maintenance including:
>
> - O&M of turbine and other plant components
> - Warranty and service contracts
> - Plant technician training
> - Condition monitoring and predictive maintenance
> - Operational issues

Sandia is supportive of these forums for participants to exchange information on the most relevant issues to wind turbine owner-operators. Reliability data and analyses can be helpful to the members and operators; the members are the audience who could benefit directly from reliability reports that address operating, maintenance, and management issues specific to wind turbines and other components.

Metrics of quality can include how well requirements, needs, and expectations are met. The utility market in part determines the wind plant requirements and needs. The expectation of reliability performance is much less defined and ultimately comes through experience. Some of the operators who have significant experience consider operations knowledge to be a competitive advantage. Others have a different attitude and consider the sharing of information to be a benefit to the industry as a whole. This is most evident when addressing issues of safety.

Sandia seeks to partner with individual companies to work toward collecting data and also for the understanding of design or O&M issues that can be improved through various means as described in the conclusions.

Section 8 - Conclusions and Recommendations

Wind turbines are getting bigger with time, in size and rated power, and this is reflected in their design.

> In general, industry estimates show that failure rates of wind turbines decrease with time. Few publications attempted to compare data provided in all…however, they all face the same challenge of comparing different topologies, placed in different sites, and with information collected in different ways…In general, literature is consistent in their conclusions about the lack availability of data, the multiple methods of data collection[9].

A long-term effort that collects data to improve reliability is needed

Improvement is not possible without sustained feedback from experiences in the field. The NRD developed as part of this project will support design standards, concepts, and component improvement.

Looking ahead for System Reliability

The future is going to be a time for incorporation of reliability tools of analysis, performance assessment, and validation or modification of design and O&M approaches. Planning efforts suggest that collaborative efforts will include the following:

Already Started

- Reliability database and systems analysis (Sandia)
- Gearbox Reliability Collaborative (NREL)

Continuing and Future Collaborations

- Design Standards and Bearing Rating
- Blade Reliability Collaborative
- Operations and Safety Research
- Reliability Centered Wind Plant Health Monitoring

And finally, it is through the identification of opportunities for technology improvements that the program will act to reduce costs and risks.

The value comes in having the opportunity to do something to prevent the failure from occurring…Thus prediction becomes part of the process of "designing the future"

Section 9 - References

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Appendix A - Database Design

The functional description of the Sandia Wind National Reliability Database is to:

a. Create SQL server Database of all wind turbine data pertaining to events, timelines, and environments
b. Establish links between event times, and environments
c. Establish rules for determining failure rates, failure causes, availabilities, and repair times from database queries
d. Determine failure rates, failure causes, availabilities, and repair times for wind turbine components
e. Perform rudimentary parameter fitting: e.g. Weibull parameter values, strengths of trends

The design of the NRD accommodates the need for multiple wind farms owned by different organizations while still maintaining the anonymity of the data supplied by those owners that do not wish to share specific knowledge of their wind farm. Even though the data is not visible to the other owners, it can be used in the calculations of aggregation of the reliability numbers (MTBF and MTTR) for similar turbines across multiple farms.

Owners will be able to control who will be allowed to see their data. This is accomplished by mapping the SQL server login ID to a unique owner identifier. The unique owner identifier is stored in the tables with wind farm specific information.

The tables are not directly accessible to any of the data partners. All data is accessed through views and/or stored procedures. The views enforce the owner access rules and allow a logged in user to see only what they are allowed to see. Some examples of views that enforce the owner access rules are as follows:

- View_Current_User
  Associate the logged in user with their unique owner index in the database.
- View_Current_User_Farm
  Provide a list of wind farm records visible to the logged in user. Also allow a new wind farm record to be added.
- Vew_Current_User_Turbine
  Provide a list of wind turbine records visible to the logged in user. Also allow a new wind turbine record to be added.
- Vew_Current_User_Turbine_Events
  Provide a list of wind turbine event records visible to the logged in user. Also allow a new wind turbine event record to be added.
- View_Current_User_Turbine_History
  Provide a list of wind turbine history records visible to the logged in user. Also allow a new wind turbine history record to be added.

- View_Current_User_Turbine_Work_Order
  Provide a list of wind turbine work order records visible to the logged in user. Also allow a new wind turbine work order record to be added.

As more data becomes available, new tables and views will likely be needed to store the different types and/or formats of reliability data. The database can easily accommodate new tables and views.

Import Process

Figure 15 shows a basic overview of the data import process.

All electronic data is imported into temporary tables specific to a SCADA vendor. There will be a set of import tables specific to each supported SCADA vendor. This process will require some work on the part of the database programming team to create a new set of SCADA vendor specific tables and write the stored procedures used to normalize the data to the final location.

The first set of tables has been defined for the Vendor X (VX) SCADA system:

- imp_Turbines_VX
  This contains the turbine history data exported from the SCADA system.
- imp_Events_VX
  This contains the event history data exported from the SCADA system.
- imp_Anemometers_VX
  This contains the environmental history data exported from the SCADA system.
- imp_Substations_VX
  This contains the electrical substation history data exported from the SCADA system.

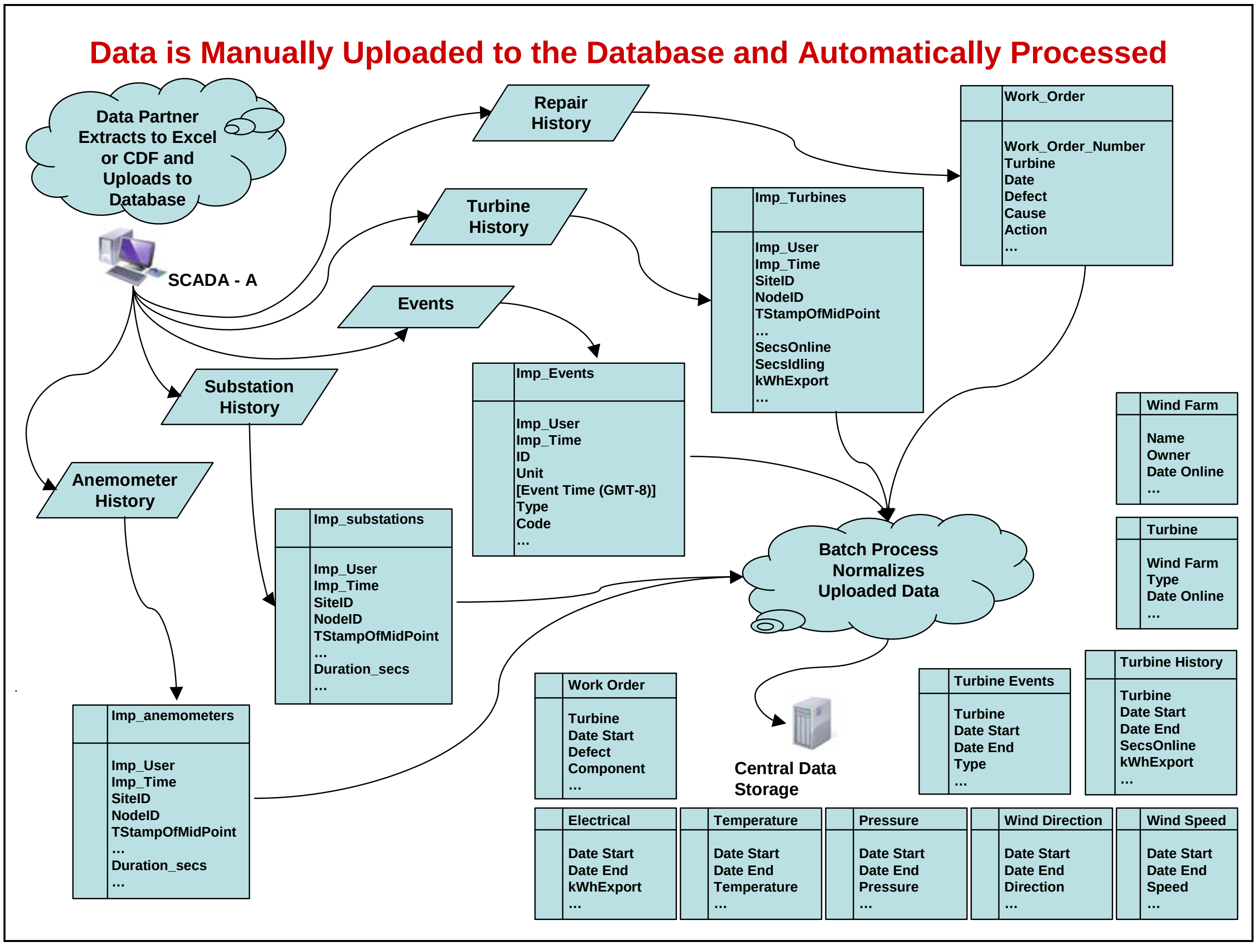


Figure 15. Data Import Process

The import process consists of four basic steps that are as follows:

1. Extract the data from the wind farm SCADA system.
2. Upload the data to the central server.
3. Normalize the data.
4. Generate new failure rates.

Extract the data

The data is extracted from the vendor specific SCADA systems to a common 3rd party format such as an Excel workbook or a character delimited file, (CDF). This format provides for the most flexibility to import the data into the central database. The process of extracting the data is highly vendor specific and beyond the scope of this document.

Upload the data

The data is uploaded to the central database via Microsoft Access project. The Microsoft Access project provides the capability to upload the extracted data directly into the SCADA vendor specific import staging tables. This is a menu driven process allowing the data partner to select the appropriate wind farm definition and navigate to the data files previously extracted. Once the data file is extracted, the data is automatically uploaded to the import tables in the central database.

Since not all SCADA data has a wind farm identifier, the specific wind farm must be selected prior to the import process. During the import process, the selected wind farm is associated with the data being imported and is stored with the uploaded data in the import tables.

Normalize the data

The uploaded data is normalized and moved to the final data tables by executing a Transact-SQL batch job. The normalization consists of removing duplicate records, calculating time ranges of events, calculating time ranges of turbine history, and calculating event overlaps.

Event records in the imp_Events_VX table consist of a time stamp, event type, event level, and indicator of whether the event is starting or ending. Calculating time ranges of events consists of matching the starting event record with the ending event record and merging the two records into a single event record in the normalized event table “Turbine Events”.

History records in the imp_Turbines_VX table consist of a time stamp for the mid-point of the history record, duration of the history record, the amount of time the turbine was running vs., idling, the amount of electricity produced, the wind speed at or near the turbine rotor, and various other indicative information about the turbine.

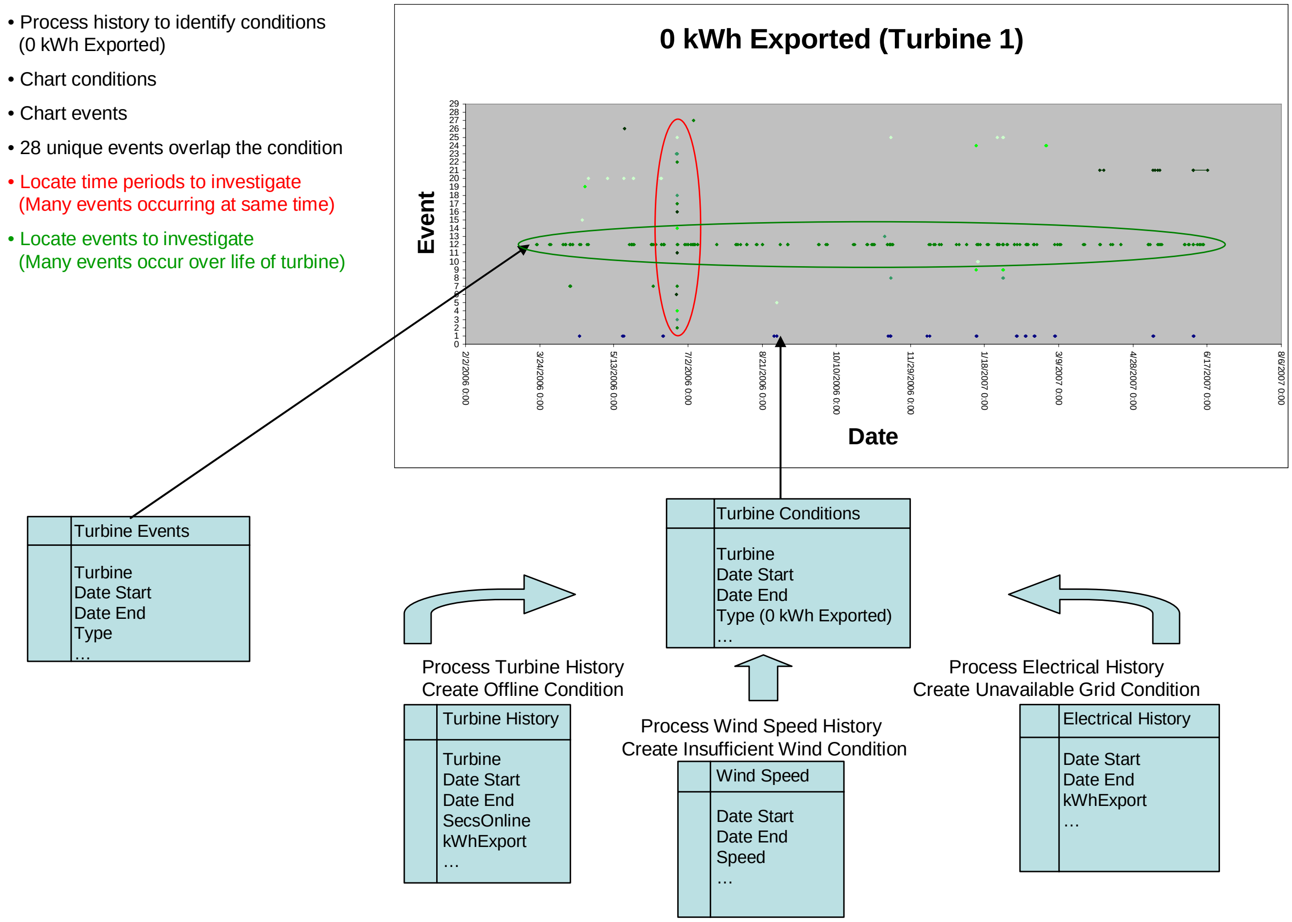
Generate new failure rates

The Microsoft Access project used to upload the data previously extracted from the SCADA system can then also be used to view new failure information based on the most recently uploaded data.

The initial implementation of the database includes correlations of failure rates with turbine components and sub-components. Failures may be defined as occurrences of events from the SCADA system (i.e. gearbox oil temp. too high, generator rotor winding temp too high) that impact availability through the need for resets or repairs. Many things including maintenance records, purchase requests for spare parts, may indicate failures.

The failures can be associated with a component or rolled up to a sub-system. The database provides the user with the ability to define the breakdown of a wind turbine thus allowing the user to control how their failure rates are calculated.

Timelines are Computed for Events and Conditions to Locate Areas of Interest



- Process history to identify conditions (0 kWh Exported)
- Chart conditions
- Chart events
- 28 unique events overlap the condition
- Locate time periods to investigate (Many events occurring at same time)
- Locate events to investigate (Many events occur over life of turbine)

Turbine Events
Turbine
Date Start
Date End
Type
…

Turbine Conditions
Turbine
Date Start
Date End
Type (0 kWh Exported)
…

Process Turbine History
Create Offline Condition

Turbine History
Turbine
Date Start
Date End
SecsOnline
kWhExport
…

Process Wind Speed History
Create Insufficient Wind Condition

Wind Speed
Date Start
Date End
Speed
…

Process Electrical History
Create Unavailable Grid Condition

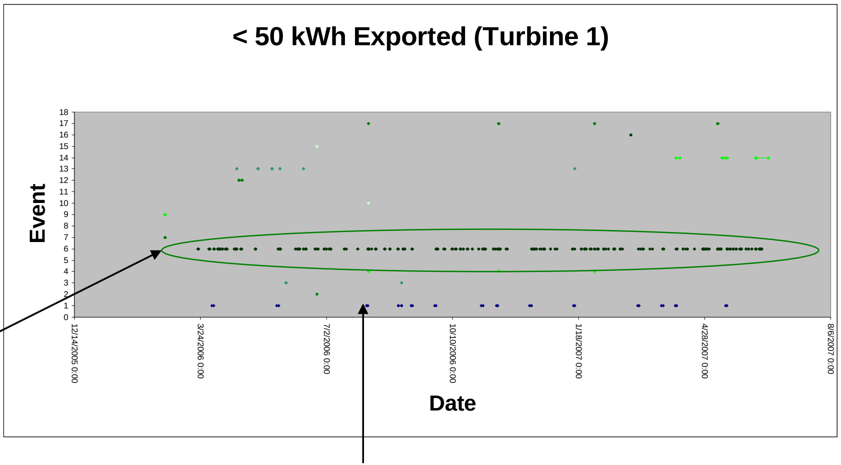
Electrical History
Date Start
Date End
kWhExport
…

Figure 16. Correlating conditions with events [Begins with charting defined conditions (i.e. 0 kWh being produced, less than 50 kWh being produced,)]

After the charts are created, events and/or time periods can be identified to investigate further.
Events are identified by looking for large numbers of entries horizontally.
Time periods are identified by looking for large numbers of entries vertically.
A condition can be some level of actual electricity production vs. potential electricity production where potential production takes into consideration many factors including wind conditions and electric grid conditions.

Timelines are Computed for Events and Conditions to Locate Events of Interest

- Process history to identify conditions (< 50 kWh Exported)
- Chart conditions
- Chart events
- 17 unique events overlap the condition
- Locate events to investigate (Many events occur over life of turbine)



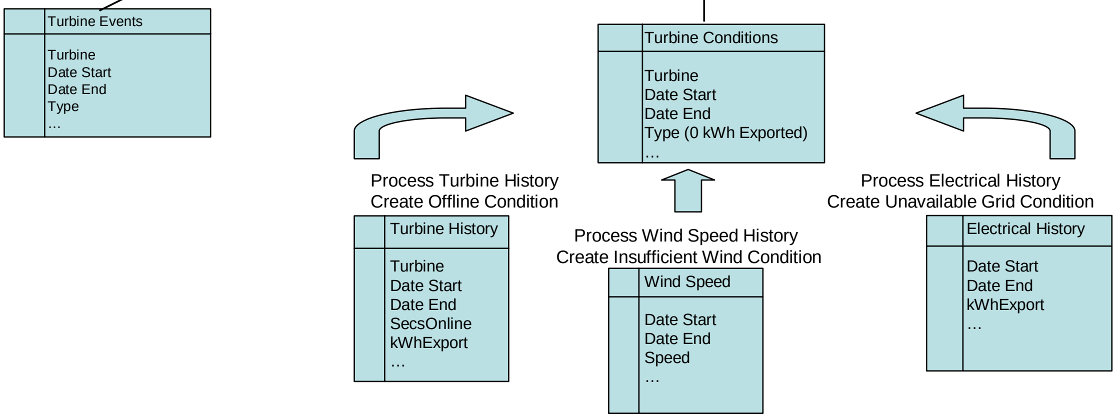


Figure 17. Less than 50 Kwh Exported Condition

The failure rates are calculated over specific intervals to allow special treatment of the three stages of failure, (infant mortality, normal, and wear out). As many intervals can be defined as needed. The components are defined in sufficient detail to allow the computation failure for specific hardware and to allow the computation of failure for groups of hardware as needed.

Appendix B – Data Plan

Reliability Data Collection, Analysis, and Reporting Plan

For

Wind Turbine Systems Reliability

Proposed by

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9/17/2007

This plan has been developed as the result of the 2006 Wind Turbine Reliability Workshop held in Albuquerque, New Mexico on October 3-4, 2006 and subsequent interactions with the American Wind Energy Association Operations and Maintenance Working Group and individual members of the United States Wind Industry. This plan has been developed so that relevant reliability data and associated information can be collected, analyzed, and reported back to stakeholder organizations and partners.

Reliability Data Collection, Analysis, and Reporting Plan

Introduction

This plan is designed to fill a need that has been identified by the owners and operators of wind turbines. That need is for better understanding of wind turbine reliability in general and specifically the turbine component failures. This will entail obtaining the metrics of failures/repairs and the estimation of the magnitude and frequency of when future failures can be expected to occur in order to efficiently plan Operation and Maintenance (O&M) activities and manage costs. The reliability analysis results will be used for a number of purposes and a central repository of baseline, integrated industry approximations of wind turbine reliability will assist in helping owners, operators, original equipment manufacturers, and other stakeholders to understand the performance of wind turbine systems, subsystems, and components and associated maintenance requirements. The results can also be used by researchers within the DOE program for identification of candidate research projects for technology improvement opportunities.

Keeping wind plants operating is sometimes problematic. Sandia seeks to use reliability analysis techniques that can contribute to overall increased reliability and efficiency, and operating cost reduction. Establishing a baseline of reliability performance is to be a key component of this effort.

Goals

A simply stated goal of the Wind Turbine Reliability Data Collection, Analysis, and Reporting Task at Sandia is to better understand and improve the reliability of wind turbines. The purpose of reliability assessment is to establish risk levels and create the knowledge base on which to build performance enhancement projects.

Detailed objectives of the program are to:

- Establish industry benchmarks for reliability performance
- Identify failure trends
- Identify industry reliability improvements over time
- Provide high quality information to support operational and maintenance practices
- Improve system performance of wind assets through better asset management practices
- Protect proprietary information and not cause harm to any party

Measures of success of this program will be:

- Representative participation of owners and operators to the larger US Industry (The larger the number of data contributors the more robust and representative the results will be)
- Participation from OEM and component manufacturers
- Establishment of efficient data acquisition interfaces and data handling systems
- Meaningful and beneficial reliability analyses and reports
- Cost effective improvement recommendations for existing systems
- Achievable reliability improvement options for future systems

Sandia National Laboratories

Sandia National Laboratories has a historic role in System Reliability Analysis for the DOE Wind Program. Sandia also has broad-based reliability capabilities derived from its engineering role in many types of mission critical systems and has developed methodologies and software tools to address a wide range of reliability problems. These tools and techniques have been applied in diverse application areas ranging from nuclear power and missile systems to aviation, automotive, and manufacturing—as well as wind turbine design loads and fatigue criteria. The wind turbine systems reliability work performed as described in this plan will be performed as part of DOE’s goals to support research and development efforts to improve efficiency and reduce the costs of wind energy technology.

Data Collection

In order to support benchmarking and analysis of issues impacting asset reliability and performance, certain data is required. The data collection process can be automated to facilitate ease of collection and communication, or may be contributed and received manually to gain specific understanding of reliability issues, or a combination of both.

Owners, operators, or others willing to share such information will provide data on failures and repairs. It is expected that it will be collected from a variety of sources including SCADA systems and other types of O&M records. Useful component failure data will include a description of the component failure, the length of time the component was in use, and the downtime necessary to repair or replace the component. Other types of information such as performance, loads, and condition monitoring data are also encouraged to be provided to establish a more complete data set. This data will also be provided according to the willingness of the owner/operator. If also available, the type of failure, e.g. overheat, foreign particle damage, oil loss/degradation, etc. will contribute to understanding and analysis.

An example of a data form developed by the AWEA O&M Working Group is provided separately.

The data set will be “anonymous” in nature and the use of the data will be governed by terms of a two-way Non-Disclosure Agreement between Owner/Operator and Sandia. Sandia will “roll up” the data and aggregate the information to be representative of the United States industry. This baseline of performance will be released but no data of an individual company will be identified with the particular source.

Sandia will collect baseline information by supporting industry groups such as AWEA who have determined that reliability is a critical issue that affects economic performance of wind production.

Efforts through this *data* collection process will be to:

- Gather
- Steward
- Organize
- Disseminate

Benefits

The investment costs for wind farm projects are high. Costs of operation and maintenance of wind turbines is partially a function of the reliability of the system components. The Reliability Data Collection, Analysis, and Reporting program will benefit owner/operators and original equipment manufactures, and other stakeholders. While these entities may have different goals and objectives for the data, the overall result will be improved asset performance and reliability. The benefits of this plan are presented:

Owner/Operators

- Benchmarking their performance relative to baseline values
- Better understanding of O&M costs/requirements
- Improved asset management and optimization
- More complete visibility into asset operations
- Risk mitigation
- Reduced Cost of Capital through more complete asset understanding

OEMs/Equipment/Component Manufacturer

- Understanding risks
- More complete dataset for benchmarking
- Better understanding of O&M costs
- Identifying candidate Engineering/Design improvements
- Increased component performance

Data Analysis

There are several metrics by which determination of system and component performance will be made, such as mean time between failures (MTBF), availability (the probability the equipment is available for use when needed), down time (the time that equipment should be operating but is not), and/or cost. These metrics will be calculated from the data submitted so that it can be used for traditional reliability and availability analysis. Failure rates, Weibull charts, reliability projections, up time, down time, availability calculations, simulation models, trending, weak links (either of design specification or maintenance processes), etc. will be produced as part of the analyses based on significance of impacts. Each data supplier will be provided an individual assessment of their overall reliability based on their system topology and data collected. In addition, an integrated industry average baseline will be created using all of the data collected and normalizing it to report standard reliability performance.

Improving equipment performance may involve improving any or all of these metrics. Sandia will quantify these metrics and determine key contributors to all of them by:

- Secure sharing of information from industry data partners
- Systematic modeling and evaluation
- Quantitative analysis for absolute or comparative evaluations
- Identification of critical failure modes and weak links

Reporting

The summary and integrated industry average baseline of reliability metrics will be reported through AWEA and other professional papers and presentations. Individual assessments from the contributors will be reported back privately. It should be noted that any information (such as comparative analyses) reported privately to the data contributors is also to be protected by the two-way NDA and therefore cannot be used for purposes of any litigation.

How to participate

1. Identify your organization as potentially being willing to be a data contributor.
2. Review your own organizations data collection processes and capabilities.
3. Contact Roger Hill (505-844-6111, rrhill@sandia.gov) to discuss participation and technical infrastructure requirements.
4. If a decision is made to proceed, execute a Non-Disclosure agreement with Sandia.
5. Determine a suitable method to provide data and proceed.

Concluding Remarks

The 2006 Wind Turbine Reliability Workshop provided significant evidence that the owners and operators have reliability concerns. Processes such as reliability centered maintenance, quality practices, reliability analysis (i.e. Weibull plots), and even simple “tracking, tracking, tracking” have been made standard business practices. The observation that everybody has anecdotes but not statistics may be overstated, but a baseline understanding of reliability performance is an obvious need.

Keeping wind plants operating can be problematic. Actions for improvement can be identified which could result in overall increased reliability and efficiency. The information will also help in defining baseline reliability expectations. Opportunities for economic improvements can be expected.

Frequently Asked Questions and Answers

- Who should supply the data?
- What data is available and needed?
- How should it be offered?
- Who will receive the data?
- How will it be handled?
- How will it be used?
- What analyses will be performed?
- How will the results be disseminated?

1. Who should supply the data?

Owners and operators who are interested in providing data that will contribute to a national model of reliability performance for wind turbines.

2. What data is available and needed?

Field failure records or aggregated component failure data is sought for all equipment that has significant reliability impacts. Mean times between failures and mean time to repair will be calculated if not provided by the data partner. Useful component failure data will include a description of the component failure, the length of time the component was in use between component failures, and the downtime and resources necessary to repair or replace the component.

Data contribution is voluntary, but the type of data expected includes:

- Failure data
- Repair / Replacement data
- Power/energy output
- Environmental conditions
- Operational condition monitoring as available

3. How should the data be provided?

The sources of data will be derived by the owner operator from SCADA records or access, report forms as may be determined, service or work order logs, parts consumption lists, O&M summaries including actual expenditures and projections, component replacement purchases, interviews, and/or expert opinions. SCADA data collection can be securely automated to improve efficiencies of data acquisition. A survey form may also be an initial form of submittal. No matter what method is used, interview with the data provider is expected. Updates will be made on a periodic basis.

4. Who will receive the data?

Sandia National Laboratories will receive the data.

5. How will it be handled?

All information identified as sensitive or proprietary will be carefully protected. Bi-directional Non-disclosure agreements are expected between the owner operator and Sandia. Any information released will be normalized to protect individual stakeholder interests.

6. How will it be used?

The data will be used for RAM—reliability, availability, and maintainability analyses and used as inputs to reliability analyses and will be held in a central repository of records. The data will be collectively aggregated to create an integrated industry average.

Analysis results may then be used for inputs to cost models, for R&D technology improvement opportunities, and as bases for examination of condition monitoring or forensic or root cause failure analyses. Increasingly sophisticated reliability analysis techniques are anticipated after the initial phase.

7. How will the results be disseminated?

Contributors will receive individual comparative analyses.

The integrated industry average baseline will be reported in conference papers, O&M user group meetings, and available on the Sandia website.

Appendix C – Reliability and Data Analysis Tools

The following pages provide summaries and comparisons of selected reliability and data analysis tools.

Comparison of Reliability and Data Analysis Tools

	System Logic Models	Other Models	Reliability Databases	Other Databases	Data Analysis	Optimization Analysis
Sandia Pro-Opta	**FT**	**Genetic Algorithm**			**Sparing, Cost, MTBF, MTTF, MTTR**	**Maintenance, Cost, Availability, Performance, Spare parts**
ARINC Raptor	**RBD**	**Availability**			**Sparing, Cost, Sensitivity, Corrective maintenance Preventive maintenance**	
Relex Reliability Studio	**RBD, FT, ET, FMECA, MLD, ESD**	**Human Factors, Markov, Maintainability**	**RAC**	**Failure Reporting & Corrective Action**	**Sparing, Cost, Weibull analysis of failure data, Uncertainty, Sensitivity**	**Maintenance, Spare parts, Repair resources**
ITEM Software ToolKit	**RBD, FT, ET, FMECA, MLD, ESD**	**Human Factors, Markov**	**MIL-HDBK-217, MIL-HDBK-472**		**Sparing, Cost, Uncertainty, Sensitivity**	
Reliasoft Blocksim	**RBD, FT, MLD, ESD**	**Human Factors, Phased demand, Duty cycle demand, Variable demand**			**Life cycle cost, Corrective maintenance Preventive maintenance**	**System reliability, Maintainability, Availability**
Reliasoft Weibull++	**RBD**			**Custom Event log**	**Weibull, Degradation analysis, Recurrence data analysis**	

Tools Comparison Summary

- All tools can interface with the SQL database rather easily. Most require a text file or Excel file to read in data. This is easily achievable with the current setup.
- Several of the tools require the construction of either Reliability Block Diagrams or Fault Trees before any analysis can be accomplished
  - BlockSim, Raptor, Pro-Opta
- Some of the tools can be purchased in an “a la carte” fashion depending on which specific capabilities are desired
  - ReliaSoft’s tools include BlockSim and Weibull++ as well as others
  - Relex has many individual modules that can work together (FRACAS, Opt/Sim, Weibull, etc…)
- Tools range from inexpensive (SNL’s Pro-Opta, $0) to very expensive (Relex FRACAS, $30K) depending on which capabilities are desired
- If simple system reliability and maintenance or sparing studies on existing database information are desired the following tools are recommended:
  - Pro-Opta
  - BlockSim (with consideration of also purchasing Weibull++ for forecasting studies)

Tools Comparison Summary

- Raptor has good basic capabilities for reliability, maintainability, availability, sparing, and cost. The drawback is that you must preprocess your data separately before inputting into the Raptor code by converting to a probability density function and fitting a distribution. If this is not a problem, then it should be considered as a reasonable option as well.
- If the capability for more complex analysis is desired and price is less of a concern then the following tools are recommended:
  - Relex (FRACAS, Opt/Sim, and Weibull modules)
    - Can basically act as the database for you without need to maintain a separate SQL setup. Does everything the other codes do with additional capabilities for interfacing with the customer, more output types, greater ability to trend data. Allows for web-based electronic submission of work orders into the database from all locations for analysis.
  - ITEM Software ToolKit
    - One price gets you the whole package, which includes capabilities beyond just maintenance, sparing, and failure analysis. Includes capabilities for analysis using FMECA, RBD, FTA, ETA, BDD, Markov, etc

BlockSim (ReliaSoft)

- BlockSim provides a comprehensive platform for system reliability, maintainability and availability analysis, reliability optimization, system throughput, life cycle cost and related analyses using the exact system reliability function and/or discrete event simulation. BlockSim models systems and processes using a Reliability Block Diagrams (RBD) or Fault Tree Analysis (FTA) or a combination of both
- All of the traditional RBD configurations and FTA gates and events are supported, along with advanced capabilities to model complex configurations, load sharing, standby redundancy, phases, duty cycles, and more
- BlockSim's simulation engine can be used to generate reliability, maintainability and availability results/plots and also for resource allocation, throughput, life cycle cost and related analyses. Flexible simulation factors include:
  - Corrective Maintenance, Preventive Maintenance (PM) and/or Inspection Policies
  - Maintenance Durations and Restoration Factors
  - Direct and Indirect Maintenance Costs
  - Availability of Spare Parts and Maintenance Crews
  - Duty Cycles
  - Throughput (constant or variable with time)

BlockSim (ReliaSoft)

- Features include:
  - Distributions available to define probabilistic values:
    - Weibull and Mixed Weibull
    - Exponential
    - Lognormal
    - Normal
    - Generalized Gamma
    - Gamma
    - Logistic
    - Loglogistic
    - Gumbel
  - Phase Diagrams
  - Maintenance Phases
  - Duty Cycles
  - Variable Throughput Models
    - Linear
    - Exponential
    - Power
  - Type I Restoration
  - Resource Usage Window
  - Analytical FRED Reports
  - Life Cycle Cost Analysis
- Using an exclusive algorithm BlockSim algebraically computes the exact system reliability function so you can obtain exact system reliability results based on component data. The software also provides the ability to set individual blocks as “failed” in order to facilitate what-if analyses. Metrics that can be obtained computationally, include:
  - Reliability and Probability of Failure
  - Failure Rate and MTTF
  - Warranty Time and B(X) Life
  - Probability Density Function (*pdf*) plots
  - Reliability Importance plots and charts

BlockSim (ReliaSoft)

- The discrete event simulation engine obtains reliability, maintainability, availability, resource usage, life cycle cost, throughput and other results. Simulation results are generated per system and/or per block (as appropriate) and “Point Results” are also available to provide a more detailed picture of the system’s operation at specified intervals across the total simulation time.
  - This information is presented in spreadsheets that support on-the-fly calculations and copy/paste. To enable further analysis and reporting, it’s easy to export the data to a BlockSim Spreadsheet (maintained independently within the same project file), ReliaSoft’s Weibull++ and/or Microsoft Excel®.
- Some of the available results include:
  - Uptime, Downtime, Mean Time to First Failure (MTTFF), Availability, Reliability
  - Failure Criticality Index, Downing Event Criticality Index
  - Quantities of CMs (failures), PMs and Inspections
  - Summaries for Maintenance Crews, Spare Parts and Costs
  - Throughput Summaries
- Results and plots based on simulation:
  - Uptime / Downtime
  - MTTFF
  - Availability
  - Reliability
  - Failure Criticality Index
  - Resource Usage
  - Cost Summaries
  - Throughput Summaries

Single User License	$2,995
5-seat Standard Network License	$11,950
5-seat Concurrent Network License	$21,650

Weibull++ 7 (ReliaSoft)

- Operates similar to an Excel spreadsheet
- Supports all “life data types” and major lifetime distributions
  - Time to failure
  - Right, left, or interval censored
  - Free-form data
  - 1, 2, or 3 parameter Weibull distributions
  - 2, 3, or 4 subpopulation Mixed Weibulls
  - 1 or 2 parameter Exponential
  - Normal
  - Lognormal
  - Generalized Gamma
  - Gamma
  - Logistic
  - Loglogistic
  - Gumbel
  - Weibull-Bayesian

Weibull++ 7 (ReliaSoft)

- Includes capability for calculating:
  - Reliability
  - Probability of Failure
  - Failure Rate
  - Warranty Time
  - Mean Life
- Includes ability to plot all of the above vs. Time or as Contour, 3D Likelihood function surface plots, or as histogram, pie, and timeline charts
- Can include confidence bounds for all life data analysis parameters
- Imports data from outside sources including MT, ALTA, Excel, delimited text files
- Can integrate directly with all other ReliaSoft software including ALTA, BlockSim, RENO, RGA, Xfmea and RCM++

Weibull++ 7 (ReliaSoft)

- Includes related analyses capabilities beyond the standard life data analysis described earlier
  - Warranty analysis (makes warranty projections based on sales & returns)
  - Reliability block diagrams (analyze competing failure modes, etc)
  - Recurrence data analysis (analyze dependent events that aren't identically distributed)
  - Degradation analysis (extrapolate failure times based on performance)
  - Non-parametric life data analysis (non-parametric life data analysis)
  - Event log interface (convert data formats for data analysis)
  - Risk analysis and probabilistic design (Monte Carlo simulation tool)
  - SimuMatic (performs large analyses on simulated data sets to investigate reliability questions)
- Reports come out print-ready so no further editing for presentation is necessary

Single User License	$995
5-seat Standard Network License	$3,950
5-seat Concurrent Network License	$7,200

Raptor 7.0

- From the Raptor website: "Raptor is a software tool that simulates the operations of any system. Raptor characterizes the system's cost, reliability, and capacity, and can highlight capacity bottlenecks, high failure-rate components, and resource hogs that are driving up the cost of your operations"
- Based on analysis of Reliability Block Diagrams. Any analysis you do within this program begins with the creation of an RBD.
- Uses Monte Carlo discrete-event simulation engine, not closed-form mathematical models to avoid creating time-consuming path-based equations for complex systems that cannot be reduced into series or parallel subsystems

Raptor 7.0

- Weak Link Analysis
- Phasing feature (allow components to change their behavior over time)
- Model failed components that induce other components to fail
- See how failures affect throughput
- Model cold and hot standby
- Perform cost, reliability, and capacity analysis
- Mimic reliability growth or decay with components that repair better or worse than new
- Model consumables and life-exhausted components
- Model components that rely on other components to operate
- Step simulations to ease verification of modeling efforts
- Delay statistics gathering to overcome startup transients
- Model subsystems as a single component, expand components to greater detail, or connect multiple RBDs
- Model the reliability and cost effects of preventive maintenance
- See the effects of failed components

Raptor 7.0

- While 18 distributions to model your data exist within Raptor, pre-processing of the data external to Raptor appears to be necessary before a distribution can be applied.
  - If raw data from life-testing or maintenance demos is to be used, it must first be converted into a probability density function with some form of curve-fitting software that outputs a best fit distribution and associated parameters
- Raptor's 18 failure and repair probability density functions include:
  - Beta
  - Binomial
  - Chi-squared
  - Empirical
  - Erlang
  - Exponential
  - Extreme Value
  - Gamma
  - Laplace
  - Lognormal
  - Normal
  - Pearson V
  - Pearson VI
  - Poisson
  - Triangular
  - Uniform Integer
  - Uniform Real
  - Weibull

Relex Reliability Studio

- Based on a series of integrated analysis modules
  - Each module can function on its own or be combined with others for a custom solution
- Relex Reliability Studio 2007 includes the following analytical tools:
  - Fault Tree/Event Tree
  - FMEA/FMECA
  - FRACAS Corrective Action
  - Human Factors Risk Analysis
  - Life Cycle Cost
  - Maintainability
  - Prediction
  - Markov
  - Optimization and Simulation
  - Reliability Block Diagram
  - Reliability Prediction
  - Weibull

Relex Reliability Studio

FRACAS Technical Highlights:

- Data Entities
  - * System tree
  - * Configurations
  - * Incident reports
  - * Maintainability reports
  - * Operating time data
- Data Linkages
  - * Reliability Prediction
  - * Weibull
- Supported Calculations
  - * Failure Rate
  - * MTBF
  - * MTTR
  - * MTMCF
  - * MTBM
  - * Custom MTB calculations
  - * Availability
  - * Cost
  - * User-defined
- FRACAS Process Support
  - * Serial numbers
  - * Workflow e-mails
  - * Data connectors
  - * ERP Integration
  - * Custom list libraries
  - * Data filtering
  - * Alert notifications
- Analysis Outputs
  - * Pareto of top (n) issues per assembly
  - * Actual MTBF per assembly
  - * Trend studies
  - * Lemon identification
  - * Reliability growth
  - * Issues per customer
  - * Issues per supplier
  - * Maintenance issues per item
  - * Top (n) warranty cost drivers
  - * Pareto of top (n) incident causes
  - * No fault found summary
  - * Total cost per problem
  - * Failure review board (FRB) agenda/minutes
- Import/Export Formats
  - * Microsoft Excel
  - * Microsoft Access
  - * Text
- Graph Types
  - * Area
  - * Bar
  - * Line
  - * Pareto
  - * Pie
  - * Scatter
  - * Stacking bar
- Report Formats
  - * Microsoft Word
  - * Microsoft Excel
  - * Adobe PDF
  - * RTF
  - * HTML
- Databases Supported
  - * Microsoft SQL Server
  - * Oracle
  - * Microsoft SQL Server Express
  - * Microsoft Jet Engine (Access compatible)

Relex Reliability Studio

- Relex FRACAS (Failure Reporting, Analysis, and Corrective Action Systems) is a comprehensive closed-loop corrective action system which enables you to collect, quantify, and control a wide range of incoming incident reports, such as test data, field data, or repair data. A FRACAS aims to control the process to ensure that product reliability and quality objectives are met. It is built around failure reports, maintenance information, and operating time data.
  - – Either acts as its own database or provides a web interface with our SQL database so the field reps could log information right into the database rather than the paper work orders that have to be made electronic later
  - – It can be set up to look just like their paper work orders then file the information appropriately
- Relex Opt/Sim takes a standard RBD process which lets you compute reliability and availability and goes a step further by allowing you to incorporate information on maintenance activities, spare parts, and repair resources. It supports calculations for:
  - – Optimal number of spares
  - – Optimal preventive maintenance intervals
  - – Optimal inspection intervals
  - – Capacity
  - – Failure Rate
  - – MTBF
  - – MTTF
  - – Reliability
  - – Availability
  - – Expected number of Failures
  - – Mean availability
  - – Total downtime
  - - Failure Frequency
  - - Hazard Rate
  - - Cut Sets
  - - Path Sets
  - - Total Cost
  - - Labor Cost
  - - Miscellaneous Cost
  - - Spares Usage Cost
  - - Spares Storage Cost
  - - Downtime Cost
  - - Cost of Initial Configuration
- Relex Weibull enables you to examine any type of failure data you have collected. Use your real-world field data to predict trends and analyze your system reliability. It supports the following distributions:
  - – Weibull
  - – Normal
  - – Exponential
  - – Gumbel - (lower)
  - - Lognormal
  - - Rayleigh
  - - WeiBayes
  - - Gumbel + (upper)

Pro-Opta (SNL)

- Assesses the reliability and availability of a system through the development of fault trees
- Specializes in producing information on MTBF, MTTR, and Mean Down Time which allows for calculation of Availability values
- Uses a Genetic Algorithm to estimate the allocation of financial resources among the feasible upgrades, spare parts strategies, and maintenance procedures in order to maximize fleet readiness
- Does not require you to fit a probability distribution to failure data
  - Do need to express uncertainty in failure rates, failure probabilities, and downtimes
  - Appears to be able to fit Gamma, Beta, Uniform, Triangular, and Empirical Distributions to data

Pro-Opta (SNL)

- Pro-Opta’s Data Analyzer imports data on events, equipment, and costs and performs statistical analyses based on distributions created for downtime and failure rates
- Allows for identification of relative cost benefits of different decisions
  - Costs for Repairable and Non-Repairable analyses can be considered
- Performance optimizations (maintenance schedules, sparing strategies, etc) can be assessed using a combination of the Fault Trees you generated and the Pro-Opta Data Analyzer file
  - Gives you top n ranked solutions and their values attained for each performance metric and constraint specified

ITEM Software ToolKit

- Integrated Reliability, Safety, and Product Life Cycle Analysis software
- Consists of the following modules:
  - Failure Mode Effects and Criticality Analysis (FMECA)
  - Reliability Block Diagram (RBD)
  - Fault Tree Analysis (FTA)
  - Event Tree Analysis (ETA)
  - Binary Decision Diagram (BDD) engine
  - Markov Analysis (MKV)
  - MainTain MIL-HDBK-472 (MTTR)
  - Spares Scaling and Ranging
  - Reliability Prediction
  - MIL-HDBK-217 (Electronic)
  - Bellcore/Telcordia (Electronic)
  - NSWC (Mechanical)
  - IEC 62380 (RDF 2000) (Electronic)
  - China 299B (Electronic)
  - Component Libraries
- Key Features:
  - 6 different Derating standards for prediction
  - 4 different failure rate Allocation models for prediction
  - Cross-module Linking and Transfer
  - Global failure model library between Fault Tree, RBD, and Event Tree modules
  - Time phasing function in Fault Tree
  - 3 different Event Importance measures
  - Critical Path discovery and cut set ranking by multiple parameters
  - 15 different, universally accepted failure model distributions for Fault Tree, RBD, and Event Tree
  - Implicit and explicit Common Cause Failure modeling
  - Dynamic modeling with Markov model linking to Fault Tree and RBD diagrams
  - Multiple FMEA standards supported: MIL-1629A, ISO 9000, IEC 61508
  - Top-down and bottom-up Design, Process, functional, or system FMEA's supported

ITEM Software ToolKit

- Add, edit and display the system information and structure in a grid, or “spreadsheet”, view. Use this table as a report by simply dragging the table to Excel, to share your analysis information
- Easily transfer any, or all, project information to your analysis. Data can move to and from Bill of Materials (BOM), Excel, Access, text and comma delimited file formats. You can also create and save import and export templates for repeated use, as well as interact with external databases

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