ELECTRIC POWER RESEARCH INSTITUTE

Assessing Remaining Useful Life of Wind Turbines

2017 TECHNICAL REPORT

Assessing Remaining Useful Life of Wind Turbines

EPRI Project Manager
L. Cerezo

ELECTRIC POWER RESEARCH INSTITUTE

3420 Hillview Avenue
Palo Alto, CA 94304-1338
USA

PO Box 10412
Palo Alto, CA 94303-0813
USA

800.313.3774
650.855.2121

askepri@epri.com

www.epri.com

3002009997
Final Report, June 2017

DISCLAIMER OF WARRANTIES AND LIMITATION OF LIABILITIES

THE FOLLOWING ORGANIZATION, UNDER CONTRACT TO EPRI, PREPARED THIS REPORT:

DNV GL – Energy

NOTE

Acknowledgments

The following organization, under contract to the Electric Power Research Institute (EPRI), prepared this report:

DNV GL – Energy
1501 4th Avenue, Suite 900
Seattle, WA 98102

Principal Investigator
A. Byrne

This report describes research sponsored by EPRI.

This publication is a corporate document that should be cited in the literature in the following manner:

Assessing Remaining Useful Life of Wind Turbines.
EPRI, Palo Alto, CA: 2017.
3002009997.

Abstract

As some of the oldest modern wind turbines are approaching the end of their design lives, wind project stakeholders are facing new questions about the right way to approach decisions around life extension. Having accurate life assessments allows decision makers to arrive at the best decisions possible and is a question of data (availability, quality, type) and method (practical, analytical). This report outlines best practices on both fronts, drawing from available literature, including standards written specifically on the topic. The physics behind a life assessment are reviewed and best practices by structural component are outlined. An economic model was developed to investigate the benefits of making investments in improving accuracy of a life assessment, and the results are presented showing a small but clear benefit to taking a proactive approach to life extension. The largest benefit was shown when a probabilistic analysis was performed so that risk-based inspections could be used to allow for continued operation past the project design life with optimally planned inspections.

Keywords
Life extension
Remaining useful life
Wind turbine

Deliverable Number: 3002009997

Product Type: Technical Report

Product Title: Assessing Remaining Useful Life of Wind Turbines

PRIMARY AUDIENCE: Wind turbine owners

SECONDARY AUDIENCE: Wind energy investors

KEY RESEARCH QUESTION

What are the current and potential future life assessment methodologies? What are the outcomes and limitations of each? What is the benefit of investing more in a more accurate analysis?

RESEARCH OVERVIEW

Research was done into the current best practices and potential future practices in wind turbine life assessment, or remaining useful life (RUL) assessment. Publicly available peer-reviewed journal articles, recognized standards, and other research were gathered and reported on. An economic model was developed and three scenarios of different approaches to assessing wind turbine life were analyzed. The results give an indication of the relative value of performing an accurate, probabilistic life assessment.

KEY FINDINGS

- Life assessments typically comprise both practical and analytical aspects.
- Physics-based modeling is the most common approach to analytical aspects of life assessment, though there are other approaches available.
- Best practices typically involve good record keeping, thorough characterization of wind regimes, access to design information, and additional monitoring of turbines.
- Performing more accurate, probabilistic life assessments has payback in terms of project net present value when numerous positive implications of an accurate life assessment are taken into account.

WHY THIS MATTERS

Wind turbine life must be addressed at some point in the life cycle. Stakeholders will be faced with questions about strategy and value in performing life assessments. This research helps decision makers facing those questions by providing information on the fundamentals of wind turbine life, analytical methods behind life assessment, an economic analysis-based look at the value of improved accuracy, and, finally, recommended best practices.

HOW TO APPLY RESULTS

The findings of this report may be of use for the following:

- Evaluation of best practice methodologies for estimation of the practical RUL of wind farm turbines and the value of performing more detailed, accurate life assessments
- Best practices on operations and maintenance record keeping, wind characterization, and structural/condition monitoring to optimize RUL estimations and cost benefit of life extension options

This publication is a corporate document that should be cited in the literature in the following manner:

Assessing Remaining Useful Life of Wind Turbines. EPRI, Palo Alto, CA: 2017. 3002009997.

LEARNING AND ENGAGEMENT OPPORTUNITIES

- Webcasts sponsored by EPRI to further explore wind turbine RUL methodologies and life extension strategies
- Participation in collaborative research and development projects related to wind turbine RUL/life extension methodologies and best practices

EPRI CONTACTS: Luis Cerezo, Technical Executive Renewables, lcerezo@epri.com

PROGRAM: Wind Generation Technology, PS-193-B

Electric Power Research Institute
3420 Hillview Avenue, Palo Alto, California 94304-1338 • PO Box 10412, Palo Alto, California 94303-0813 USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com

List of Abbreviations

Abbreviation	Meaning
AI	artificial intelligence
ANN	Artificial neural networks
CFD	computational fluid dynamic
CMS	condition monitoring system
DEL	Damage equivalent loads
DLC	design load cases
EBoP	Electrical Balance of Plant
EU	European Union
FORM	first order reliability method
GW	Gigawatt(s)
IEC	International Electrotechnical Commission
IRR	internal rate of return
ISO	International Standards Organization
LDD	Load duration distribution
Lidar	light detection and ranging
MTBF	mean time between failures
MW	Megawatt(s)
NDT	non-destructive testing
NPV	net present value
O&M	Operations and maintenance
OEM	original equipment manufacturers
RBI	Risk based inspections
RUL	remaining useful life
SCADA	supervisory control and data acquisition
SHM	structural health monitoring
SORM	second order reliability method
TI	turbulence intensity
US	United States

Table of Contents

List of Figures

List of Tables

Section 1: Introduction

The practice of leveraging the power in the wind to generate electricity is not new. Three-bladed, horizontal axis wind turbines have been commercially produced and operated in notable numbers since the early 1980s. However, while wind turbines being installed today still look similar to earlier versions, much has changed over those three decades. The most obvious change is the increase in size: from the 1980s to 2015, the average hub height grew from 18 m to 82 m and the average rotor diameter grew from 17 m to 102 m [1]. That change represents greater than a four-fold increase in hub height and six-fold increase in rotor diameter in about 30 years. In order to keep up with this impressive growth rate, designs have had to evolve as well. The gains in turbine size can largely be attributed to: advances and optimization in blade design and materials, advanced controls approaches, use of power electronics, and standardization and improvements in analysis and design tools and methods.

Installed capacity has followed a similar growth trend. Growth in the wind industry has been in the double digits for almost 20 years, and forecasts do not expect it to slow down. By the end of 2015, Global Wind Energy Council reported a total installed capacity of 433 GW worldwide [2].

The United States (US) has followed the strong growth pattern: in the US, wind power saw its start in California in the 1970s and 1980s. Since 1998, the average nameplate capacity of wind turbines in the US has increased by 180% (the 2015 average was 2.0 MW) [3]. In the last five years wind energy accounted for 30% of all newly installed generating capacity; this growth has culminated in a total installed capacity of 74 GW by the end of 2015 [4].

In the European Union (EU), the picture was largely the same: wind installations accounted for more new capacity in 2015 than any other source of energy. The total installed capacity in the EU was 142 GW by the end of 2015 [5].

With a typical design life of 20 years, owners are increasingly concerned with the remaining useful life (RUL) of their wind generation assets. In the US, some of the older megawatt-scale turbines are 15-18 years old, and about 8,000 MW are more than 10 years old. By the year 2035, all of the US's current fleet (74 GW) will be over 20 years old and fully all of the EU's 142 GW will also be over 20 years old. In the EU, about 12 GW are currently more than 15 years old, and about 28 GW are more than 10 years old. These trends are shown in Figure 1-1 [4, 5].

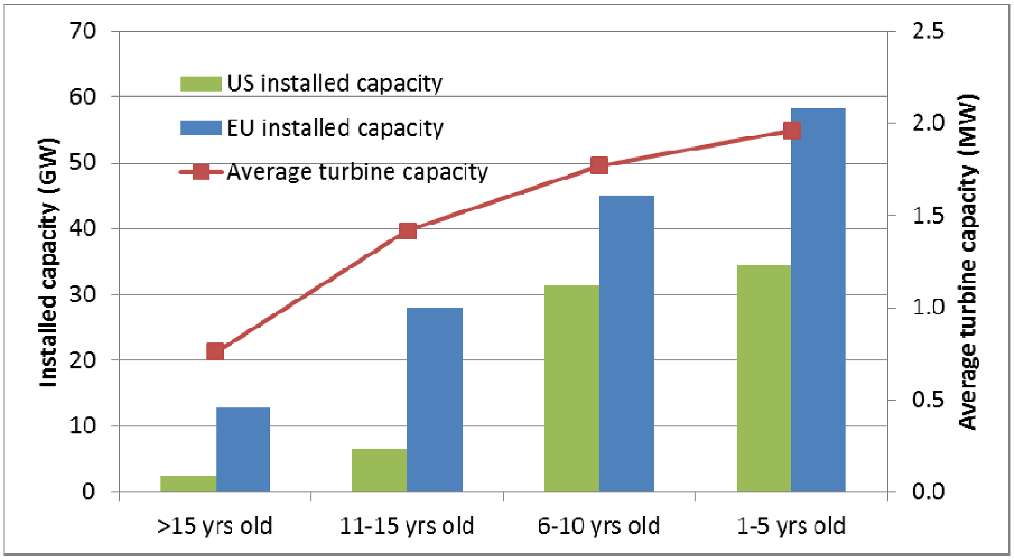


Figure 1-1
Installed capacity and turbine capacity of US and EU turbines by age as of 2016

Many smaller turbines have been operating in California for over 20 years; some lessons can be taken from these cases; however, these turbines were largely designed to a different set of standards and, as such, long-term reliability of these older turbines is not a useful predictor of reliability of modern turbines.

These trends set the stage for a significant need in the wind industry to manage risks associated with aging assets, and in particular, with managing risks around continued operation past turbine design life. This report discusses the various approaches to one aspect of asset life extension for wind turbines: assessing structural reliability. RUL is used throughout this report to refer to the remaining time (or time from commercial operation) a wind turbine or wind farm is expected to be able to operate. These expectations are based on the remaining fatigue strength of the structural components of a wind turbine (as described in Section 10). However, in practice, project stakeholders may choose to operate a wind turbine for a shorter time based on:

- Project economics
- Availability of engineering support available from original equipment manufacturers (OEM)
- Operations and maintenance (O&M) costs including component and Electrical Balance of Plant (EBoP) failure rates
- Supply chain
- Decommissioning and repowering strategies including potential evolution of wind turbine technology and associated capital costs
- Power purchase agreements

- Future interconnection and grid compliance requirements
- Future tax credits
- Permits and land owner agreements

These other factors affecting decision making around life extension are not covered in this report. This report focuses on structural aspects to RUL assessment.

Approach to Life Extension

Even if maximum load is well within the design limits, if exposed to cyclic loading for long enough, all wind turbines will eventually experience structural failure. Structural failure is an event in which a structure can no longer resist the loads it experiences; in other words, it is the loss of load-carrying capability. Examples of structural failure are: a severely cracked or debonded blade, a cracked hub or mainframe casting, or a cracked tower weld.

Allowing a structure to catastrophically fail or collapse is undesirable for many reasons, including exacerbated economic loss, potential impacts to human safety, environmental damage, secondary property damage, and associated public relations implications. There have been a limited number of catastrophic failures of modern wind turbines. The manner, consequences, and setting in which they fail factor into the degree of undesirable impacts. For example, if a wind turbine collapsed near homes, other structures, or roads, the public and landowner relations will likely be impacted more than if one collapsed offshore.

The risk of catastrophic failure can be mitigated by (1) decommissioning the structure when the calculated probability of failure exceeds a certain level, or (2) monitoring the structural integrity through inspections and decommissioning when there are material indications of imminent failure that are too costly to repair or cannot be repaired (such as ductile iron castings). There are challenges and shortcomings with both approaches; but the two approaches can also be complementary and can be used in conjunction. Operating strategies (such as derating) can also reduce the fatigue loading and thus reduce the risk of failure, but they need to be implemented early in the project life to make a substantive impact on asset life extension.

When turbines are originally designed and certified, they must demonstrate a minimum design life. This is most commonly 20 years. Wind turbines have been operated well past 20 years, without re-certification for a longer design life; however, it is more risky to continue operation without certification. The risk of structural failure increases with every year of operation, and when operating past the design life it is more likely the design loads (and therefore cumulative fatigue damage limits) will be exceeded; if it can be obtained, certification provides a higher level of assurance against structural failure.

Wind turbines certified to a design standard are expected to be capable of withstanding extreme and fatigue loads that would be generated by the wind conditions prescribed for the wind turbine class[1]. However, because of the complexities of commercial and technical design tradeoffs, for example in the case of turbine “platform” product development, many components may be designed to withstand higher loads than those generated by just one wind inflow class. This may imply an additional design margin above that achieved by application of the required safety factors and loading for a given component and its International Electrotechnical Commission (IEC) design wind class.

Some jurisdictions may come to require re-certification to operate past the turbine design life. In Germany, it is required that a third party perform structural and functional inspections regularly. There are two standards relevant to the continued operation of wind turbines:

- DNV GL Service Specification: DNVGL-SE-0263 Certification of lifetime extension of wind turbines, March 2016 [6].
- DNV GL Standard: DNVGL-ST-0262 Lifetime extension of wind turbines, March 2016 [7].

Between these two standards, guidance is given for certifying extended operations through RUL assessment, including practical and analytical aspects and optionally probabilistic aspects. These approaches are detailed next in Section 2.

The time line of performing life assessments and developing inspection plans are not provided in [6] or [7]. However, [6] provides some sample timelines:

- Example 1, five turbine wind farm: SCADA data and wind measurements are collected starting 4 years prior to end of design life; load simulations are performed and an inspection plan is reviewed by DNV GL half a year before the wind farm reaches the design life.
- Example 2, 90 turbine wind farm: SCADA data and wind measurements collected seven years before the end of the design life; loads measurements are performed at three turbines; the process of collecting and analysing life from SCADA data and wind measurements is repeated four years prior to the end of the design life to confirm initial analysis; one year before the end of design lifetime, DNV GL evaluates the inspection plan and results of one round of inspections.

[1] Wind turbine class is defined by the IEC 61400-1 through designations of wind speed and turbulence parameters. The design lifetime is prescribed as at least 20 years.

Section 2: RUL Technical Assessment Methods

In this section, technical approaches to assessing RUL for a specific wind farm are discussed. The scope of the discussion is limited to structural turbine components unless otherwise stated. In general, approaches can be split into two assessment categories: practical and analytical. The practical assessment involves inspections, review of operational and maintenance history, and review of field experience with a specific turbine model. The analytical assessment involves calculation of site and design loading to determine the year in which the site loads exceed the design loads. It may or may not include a probabilistic aspect. Due to uncertainties in fatigue data, theory and applications to wind turbine RUL analytical assessment, a practical aspect of RUL assessment should also be undertaken.

RUL Assessment Overview

Reliability is defined according to International Standards Organization (ISO) standard 2394, *General principles on reliability for structures* [8] ("ISO 2394") as the "ability of a structure or structural element to fulfill the specified requirements, including the working life, for which it has been designed." A **target or design reliability level** can be thought of as the inverse of probability of failure: the lower the probability of failure the more reliable a structure. The target reliability level is determined for each type of structure through consideration of various factors including the consequences of failure to human safety and the environment, economic loss and social impacts, and the cost of measures to reduce the risks of failure.

Structural **design life** can be defined as the number of operating years after which the actual reliability level is expected to drop below the target design reliability level under specified design conditions (typically designated by turbine class). Said differently, if a wind turbine is designed to a cumulative probability of fatigue failure of one in a thousand ($1x10^{-3}$), then the design lifetime is the year at which the expected probability of failure reaches $1x10^{-3}$ (if the site conditions perfectly reflect the IEC design inflow conditions, then often after 20 years). The probability of fatigue failure is zero at inception and increases exponentially over time.

Because there are currently no laws in the US addressing reliability of wind turbines, it is up to the stakeholders to decide what risk they are willing to assume in the continued operation at structural reliability levels lower than the design reliability level. Potential stakeholders include owners, lenders, insurers, utilities, and the public.

The term **site design life** can be used to represent the number of years from inception to reach the design reliability level under site conditions that may be more or less severe than design conditions. In other words, the site design life is the number of years a turbine can operate in a *site specific wind regime* before the fatigue loading (and the resulting cumulative fatigue damage) on the major structural components exceeds the fatigue loading that would be experienced in the *specified design wind regime*. The **RUL** is the number of years between the current year of operation and the site design life (remaining years until the end of the site design life).

While this report is focused on structural components with all approaches to RUL assessment, in addition, the control system and electrical equipment listed in Table 2-1 must be considered.

Table 2-1
Components and parts to be included in a RUL assessment [7]

Component/System	Parts
Rotor	Blades*
Machinery components	Hub* Main shaft* Torque arms* Main bearing housing* Mainframe* Rear frame Spinner and nacelle cover Pitch system Main bearing Gearbox Bolted connections Yaw system*
Tower	Tower segments* Tower connections* Tower door frame*

* indicates structural component

Table 2-1 (continued)
Components and parts to be included in a RUL assessment [7] (indicates structural component)*

Component/System	Parts
Foundation	Anchor bolt connection* Embedded steel section* Slab foundation* Pile foundation* Jacket structure (offshore)* Monopile structure (offshore)* Grouted connection (offshore)*
Control and protection system	Sensors Braking systems Control software
Electrical equipment	Generator Lightning protection Cabling Power converters

* indicates structural component

In general, with discussion of lifetime of a structure, the fatigue is the failure mode of concern because the probability of failure due to fatigue loading increases with time. Reference [15] describes fatigue failure as the result of initiation and propagation of a crack until the crack becomes unstable and propagates fast, if not suddenly, to failure. There are multiple ways to assess the likelihood of fatigue failure.

Analytical Assessment

The analytical assessment consists of a calculation to evaluate the fatigue life of the turbine structural components. This most likely involves a physics-based model but alternative approaches exist including stochastic models, data-driven/artificial intelligence (AI) models, and combined models [8, 9]. Each is discussed in Section 5.

Regardless of the modeling approach, any analytical assessment should consider the following:

- Uncertainty: estimating life of a component is a necessarily uncertain endeavor. Uncertainty should always be considered and accounted for in any analytical assessment.
- State of the art: if the RUL assessment is happening well after the turbines were designed, the codes and tools will likely have progressed significantly since the design was performed. Though it may require additional modeling and analysis effort, state of the art tools should be used in the assessment.

- Analysis despite lack of design information: if design information is not available, [7] states it is acceptable to use a generic turbine model.
- In all cases, the key environmental conditions the turbines are exposed to should be considered. These include wind speed distributions, turbulence intensity, wakes (including impact of wakes on turbulence intensity), complex terrain, air density, and shear.
- In more advanced analysis, additional environmental conditions may be considered such as temperature trends, humidity, salinity, soil conditions, and ice.
- Extreme loads do not need to be assessed because the risk remains the same in extended operations as it was during the design life.

Though other methods have promise, common practice today is to use physical models alone or in combination with statistical models to calculate RUL, thus unless otherwise specified, when discussing analytical assessments for RUL calculation in this report, a physical model is assumed.

Practical Assessment

The purpose of the practical assessment is to identify any signs that the life of the wind turbine may be limited due to the existing turbine condition, or any historical maintenance or operations practices out of line with best practice or the OEM instructions. The practical assessment includes a document review and inspections for condition and damage.

Document Review

The document review provides the analyst with an understanding of the design, expected condition, historical issues, inflow conditions, and so on. The document review should ideally include the following, though some may only be available to the OEM [7]:

- Technical information about the wind turbine:
  - Turbine type, manufacturer, configuration, control and braking system, rotor blade type, design lifetime, wind class
  - Approval documents (type approval, type certificate, site specific design assessment or equivalent)
  - Design calculations, design drawings, design specifications
  - Assessment and certification reports (load assumptions, rotor blades, machinery components, control and protection system, tower, foundation, electrical installation)

- Construction and commissioning records:
  - Commissioning reports
  - Building permit
  - Site map
- Preconstruction wind resource measurements and energy analysis reports
- Operational data including energy production, site specific wind statistics, and availability
- Maintenance records:
  - Operating and maintenance manual
  - Inspection reports (periodic monitoring and other inspections)
  - Documentation on failures and incidents as well as modifications, repairs, exchange of components
- Foundation design documents including:
  - Geotechnical report
  - Foundation loads
  - Design calculations

Inspections

Inspections include both an initial assessment inspection and an inspection plan for ongoing inspections that continue through the remainder of the operating period. The analytical assessment informs the inspection plan. Inspections are performed to identify or test for damage, cracks, pre-stress, fit/tightness, function, corrosion, oil level and wear (as specified per component in [7]).

The scope of the inspections will vary depending on site specifics, the results of the analytical assessment and life extension strategy. An example of a more detailed plan would include the following:

- Turbine specific risk based inspection plan interval, inspection method and scope
- Visual inspection of all load-transferring and safety related components
- Function tests (for example, braking, alarm detection)

These inspections can be coupled with a data review including maintenance and inspection reports, supervisory control and data acquisition (SCADA) data, and turbine model field experience.

Risk based inspection (RBI) is a formalized method to integrate knowledge from the analytical assessment, any inspections performed, and historical information about the project. The RBI process includes analyzing project specifics to map out the following aspects:

- Risk of structural failure for each component as determined from models and data available to perform structural reliability analyses and model crack growth
- Inspection technology available including its capability to detect damage early
- Costs associated with inspections, repairs, maintenance, and continued operation
- Target reliability levels (a reflection of stakeholder risk appetites)

From this mapping, intentional inspection plans can be developed in a qualitative or quantitative optimization (depending on data available) that will maintain risks below a target level by catching cracks before they reach a critical length, and thus allow for continued operation in spite of uncertainty in analytical approaches to predicting turbine operating life.

The concept involves combining an analytical assessment of the risk of failure with inspections that can be used to update that assessment with the additional knowledge gained from the inspection, whether damage is found or not found. The classic example is to use crack growth modeling in combination with inspections for cracks. If the model predicts the probability of cracks of certain lengths, an inspection that discovers no cracks can potentially reduce the probability of at least the largest cracks (those that the specific inspection technology can detect), allowing for a reduction in the risk.

Section 3: RUL Analytical Assessment for Wind Turbines

The general approach typically taken for an analytical RUL assessment involves using a physical model of the turbine fatigue behavior, sometimes including a statistical model. The data often used in the analysis include:

- **Pre-construction meteorological (met) data**. Wind speed, turbulence intensity, shear, air density, inflow angle measurements across the site made before turbines were installed and commissioned.
- **Operational data**. Failure rate data for the site and/or for the turbine model fleet performance; SCADA data like turbine wind speed, power generation, rotor speed, blade pitch, turbine state, and so on; on-site met data.
- **Basic design basis**. International design standards designed to; design class; basic turbine architecture.
- **Detailed design basis**. Structural design load margins; component hot spots; design specifics.
- **Additional measurements**. Load measurements; condition monitoring system (CMS) data; structural health monitoring (SHM) data.

The steps involved for calculating RUL for each turbine are [14]:

1. **Characterize inflow**. Define the lifetime environmental condition distributions at the turbine location (including correlations if possible) including turbulence intensity (TI), wind speed, shear, air density, inflow angle. Adjust if needed for terrain and wake effects.
2. **Site loads**. Use a physical model to calculate the turbine site loads on either a relative or absolute basis under the environmental conditions expected at the turbine location.
3. **Load margins**. Compare the turbine site loads to component design loads or strengths either deterministically to get site load margin or through a probabilistic limit state analysis. If available, combine site load margin with design margin to determine total load margin. See Appendix A for load margin definitions.

4. **RUL or probability of failure**. Calculate the RUL of each component:
   a. If using a deterministic analysis, RUL is the year at which the structural reliability under site loads reaches the same reliability in the design life under design loads.
   b. If using a probabilistic limit state analysis, calculate probability of failure by year, then compare against the target reliability to identify the operating year in which the site reliability drops below the target reliability (which designates the component-specific site life).

Below some specific approaches are explored for scenarios of limited information.

RUL Assessment as a Function of Available Information

The specific approach taken to assess RUL for any given wind farm will be highly dependent on the information available. The more information available, the more accurate the assessment can be; however, some information may not be available to owners, and some information may have been lost in ownership transition. Best practices for recording and maintaining the right data and of the appropriate quality for RUL assessment is detailed in Section 8. This section identifies the approach that can be taken given various scenarios of quantity and type of data available. All scenarios assume, at minimum, pre-construction met data and the basic design basis is available. If the basic design basis is not available, it is not possible to calculate RUL. If pre-construction met data are not available, operational met data may be enough to calculate RUL but the accuracy would be insufficient for most uses.

Scenario 1: RUL Assessment Without Operational Data or Detailed Design Basis

If the pre-construction met data and *basic* design basis are available but no additional information is available (*detailed* design basis, as defined above, is not available), the analytical assessment can be performed with some assumptions. Using the same steps as listed above, the method is outlined below:

1. **Characterize inflow**. Define the lifetime environmental conditions at the turbine location using pre-construction data and wind flow modeling (computational fluid dynamic (CFD) models to improve accuracy). Use long-term (measured or modeled) wind data in the region to extrapolate measured data to lifetime estimates.
2. **Site loads**. Use a generic turbine aeroelastic model to calculate the turbine site loads under the environmental conditions expected at the turbine location. The generic turbine aeroelastic model should have the same general turbine architecture as the site turbine model, including the same general control scheme, such as variable speed, pitch controlled, or independent (cyclic) pitch control for load mitigation. The absolute loads calculated from a generic model are not applicable to a different turbine model, but site load margins (relative loads) are accurate enough for a RUL assessment.

3. **Load margins**. Calculate design loads using the same generic turbine aeroelastic model as in Step 2. Use design inflow conditions as model inputs. Compare the turbine site loads to component design loads either deterministically or through a probabilistic limit state analysis. The design margins are assumed to be zero because detailed design basis (as defined above) information is not known.

4. **RUL or probability of failure**. Calculate the RUL of each component:

    a. If using a deterministic analysis, RUL is the year at which the structural reliability under site loads reaches the same reliability in the design life under design loads. This can be done using Miner's rule:

    $$Site\ life = Design\ life\ *\ {\frac{Site\ load}{Design\ load}}^{-m}$$

    where the exponent "m" is the Wohler exponent appropriate to the material , as described in Section 5.

    b. If using a probabilistic limit state analysis, calculate probability of failure by year, then compare against the target reliability to identify the operating year in which the site reliability drops below the target reliability (which designates the site life).

Scenario 2: RUL Assessment With Operational Data but Without Detailed Design Basis

If the pre-construction met data, *basic* design basis, and operating data are available but no additional information is available, the analytical assessment is similar to Scenario 1, but Step 1 (characterizing inflow) can be made more accurate using the operating data.

Inflow characterization can be updated using various optimal updating or Bayesian updating techniques as more information is made available throughout the operating period. The following steps can improve the understanding of site loading:

- **Wind speed**. Turbine specific wind speed can be updated using operating data by evaluating the energy output for each turbine; a wind speed distribution shape and power curve must be assumed to extract mean wind speed. The wind speed distribution shape can be updated if unwaked met tower data are available in the operating data set. Alternatively, some turbine controllers calculate a free-stream wind speed based on measured variables (particularly nacelle based wind speed) and a model of the turbine. If such free-stream estimates are available in the operating data, they can be used to update wind speed estimates.
- **TI**. If unwaked TI is available from a permanent met tower, relationships can be developed with the nearest turbine nacelle-based TI measurements. These relationships can then be applied to other wind turbines. This approach is challenging, and whether or not it results in more accurate estimates of TI depends on the specifics of each site.

- **Operating conditions**. Actual operating conditions that vary from assumptions could have a notable impact on fatigue load calculations. For example, if a wind sector management program was not implemented correctly, accounting for the actual operations in the RUL assessment may be important. Alternatively, turbine downtime can be accounted for when operating data are available. Downtime due to high or low wind speed is already accounted for in Scenario 1, but downtime due to other reasons such as curtailment can now be accounted for as time the turbine is not experiencing operating loads.

In conclusion, operating data can typically be leveraged through making better estimates of inflow conditions by updating pre-construction estimates. However, it has limits and cannot fully replace pre-construction estimates.

Research has been done into using standard SCADA channels to estimate fatigue loads directly [9], which has promise but require turbine model specific data. In most cases, this data would be expensive to gather (like through a loads measurement campaign), or would be proprietary to the turbine OEM. In cases where a power performance test has been performed (or other cases where a hub height or taller met tower is installed close to and upwind of a turbine in flat terrain), an owner may have enough data to utilize a neural network approach to estimating free stream wind speed and TI. Such a scheme is presented in [9], with 0.5% mean error on wind speed and 4.5% on standard deviation of wind speed. While such methods show promise, more research is needed.

Scenario 3: RUL Assessment With Operational Data and Detailed Design Basis

In a scenario where all the information from Scenario 2 is available plus *detailed* design basis information will be more accurate because some assumptions and simplifications are no longer needed:

- Step 2, calculating site loads, can be done more accurately because an aeroelastic model of the exact turbine type being considered can be developed and used instead of a generic turbine model.
- Step 3, calculating load margins, can be done more accurately because nonzero design margins can be accounted for.

Scenario 4: RUL Assessment With Operational Data, Detailed Design Basis and Additional Measurements

A scenario where all the information from Scenario 3 is available plus additional measurements is going to result in the most accurate RUL assessment of the four scenarios. Additional measurements that would be of use include load measurement campaigns, CMS, and SHM data.

Site specific loads measurement campaigns comprise some set of loads measurement sensors installed temporarily or permanently on turbine structural components. These data can be utilized in a number of ways to complement RUL assessment:

- Loads measurement data can be used to calibrate aeroelastic models and correlate to SCADA data, reducing uncertainty. Data can be collected over a short period of time (less than a year) and can be collected on one or two turbines.
- If a turbine has experienced unusual operating conditions or environmental conditions, measuring the loads during these conditions will provide the analyst with very accurate estimates of structural loading.
- Permanent load sensors are challenging to maintain but can be used to give the most accurate (and near real-time) fatigue cycle counting.

The challenge with loads measurement campaigns is that a *detailed* design basis must be known to make use of the data in most applications.

Traditionally, CMSs comprise sensors that monitor signals such as vibrations, accelerations, temperatures, particle count in a filter, and so on, and are most applicable to monitoring the condition of drivetrain components. This information is typically used to identify failures in progress. For example, a gearbox which has started to fail via gear pitting would likely exhibit early signs through increased vibrations, increased temperature and increased particle count in the gearbox lubricant. Fan, et. al., for example, demonstrated an approach to predicting a gearbox failure underway through particle count data [13]. While CMS are useful for predicting imminent failures once the failure mode has initiated to the point that there are warning signs, they are not as useful for predicting how long a part will last. One exception is in components whose life depends on thermal cycling, such as electrical components: temperature monitoring can contribute to more accurate estimates of site design life for these components.

CMS are regardless, a useful tool for running turbines longer because early failure diagnostics will help prevent secondary damage when a part fails.

SHM is a broad term that encompasses measurements that monitor a metric that indicates structural health. An example is acoustic emissions monitoring: the acoustic signature of a structure under normal operation is recognized such that when the acoustic pattern varies due to a crack formation or growth of a crack, a notification is made. While this has been an area of research it is not widely used. It would also fall into the same category as CMS in that it may at some point be a useful tool for identifying failures once they have initiated but before they propagate through to full failure, but it would be difficult to use SHM data to inform RUL. However, decisions about SHM investment could be informed by RUL assessments, leading to a more robust life extension through the combined approaches.

RUL Analytical Assessment Conclusions

Even with this most accurate assessment, there are still sources of uncertainty, including:

- Uncertainty in the material strength: there is a distribution of strengths expected for any material manufacturing process.
- Modeling uncertainty: there is uncertainty in any mathematical simplification of a physical phenomenon.
- Measurement uncertainty: there is uncertainty due to sensor inaccuracy, calibration drift, temperature effects, and so on, in any measurement feeding the analysis.
- Uncertainty due to natural randomness or un-modeled factors: there may be an inherent randomness in a physical phenomenon that we are modeling and there may be factors impacting the phenomenon that we have not modeled. Both of these add to uncertainty in our results.

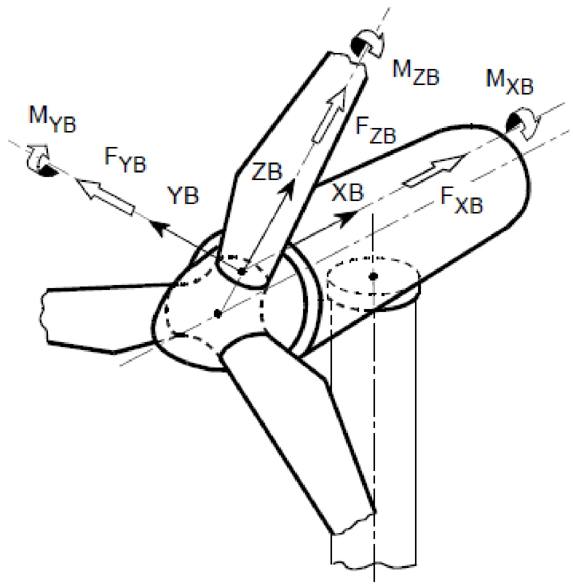
Section 4: RUL Assessment for Key Wind Turbine Components

The various structural components of a wind turbine might be designed differently, subject to different loading, and there may be varying levels of detailed information available to a wind turbine owner. For these reasons, approaches for RUL assessment can vary by component. In this section we outline best approaches for evaluation of the RUL for rotors, drivetrain components, towers, foundations, general condition and finally, for health and safety. But first it is helpful to review primary structural load pathways.

Load Pathways

The primary loading originates on the rotor due to aerodynamic, gravity, and inertial loads; the typical load path from the blades travels through the blade bearings, bolted connections, and into the hub; the hub carries the combined loads of the three blades into the main shaft. The main shaft loads are reacted by the main bearing housing and gearbox housing (depending on drive train architecture); the housings are connected to the mainframe of the machine which transfers the loads to the yaw system. The yaw system transfers the loads to the tower and finally through the foundation to the soil.

The loads considered in a loads analysis include the forces and moments in three axes in different coordinate systems depending on the component of interest. For example, blade loads are considered in coordinate systems aligned with sectional principal axes along the span and at each blade root, as shown in Figure 10-1, where “F” indicates force and “M” indicates a bending moment (an eccentric force acting to bend the element). Hub and tower coordinate systems are shown in Figure 10-2 and Figure 10-3. The important load components considered in a RUL assessment are listed, described, and drivers identified in Table 4-1. In Table 4-1 the material is indicated for each load because this determines the slope of the fatigue strength curve used to evaluate damage equivalent loads (DEL)s.



XB in direction of the rotor axis
ZB radially
YB so that XB, YB, ZB rotate clockwise

Figure 4-1
Blade load coordinate system

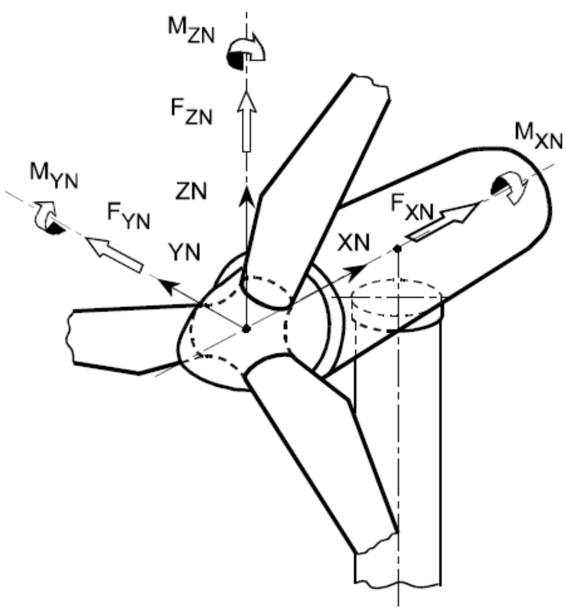


Figure 4-2
Hub load coordinate system (coordinates rotate with rotor)

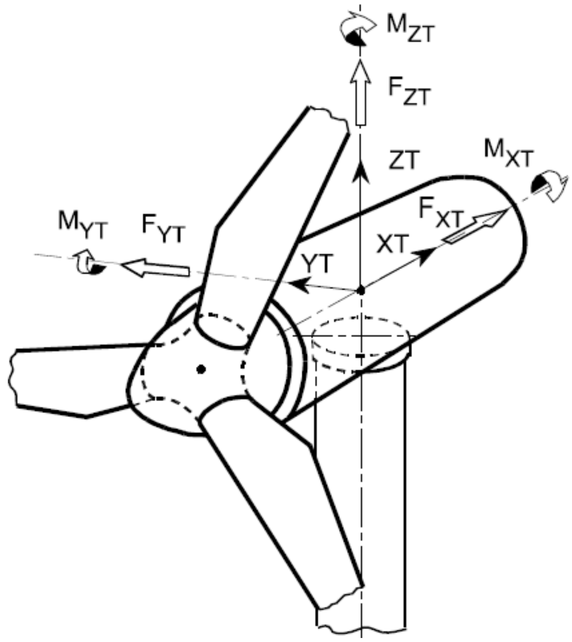


Figure 4-3
Tower load coordinate system (coordinates are fixed)

Table 4-1
Key load elements

Load Element	Description	Turbine Components	Fatigue Load Driver
Blade edge bending, 50% span (fiber glass)	The moment acting on the blades along the edgewise direction (M_{XB} in Figure 4-1 at the midway point between root and tip.	Blades	Primarily driven by gravity loads from the weight of the blade outboard section and therefore sensitive to wind speed distribution (operating hours). Some contribution from varying aerodynamic forces.
Blade edge bending, root (fiber glass)	The moment acting on the blades along the edgewise direction (M_{XB} in Figure 4-1) at the root.	Blades	
Blade edge bending, root (steel)	The moment acting on the blade root connection to the hub along the edgewise direction (M_{XB} in Figure 4-1).	Blade bearings, blade bolts, hub	
Blade flap bending, 50% span (fiber glass)	The moment acting on the blades along the flapwise direction (M_{YB} in Figure 4-1) at the midway point between root and tip.	Blades	Primarily driven by aerodynamic loads and therefore sensitive to annual TI distribution, shear, air density, and wind speed distribution.
Blade flap bending, root (fiber glass)	The moment acting on the blades along the flapwise direction (M_{YB} in Figure 4-1) at the root.	Blades	
Blade flap bending, root (steel)	The moments acting on the blade root connection to the hub along the flapwise direction (M_{YB} in Figure 4-1).	Blade bearings, blade bolts, hub	
Shaft thrust (steel)	Thrust force acting on the drive train (F_{XT} in Figure 4-3).	Hub, main bearing housing, gearbox housing, mainframe	Primarily driven by aerodynamic loads and therefore sensitive to annual TI distribution, air density and wind speed distribution. Less sensitive to shear than other load components because observed in the fixed coordinate system where shear does not have a cyclic impact.

Table 4-1 (continued)
Key load elements

Load Element	Description	Turbine Components	Fatigue Load Driver
Shaft bending (steel)	Bending moment as applied by the hub to the shaft and reacted through the drivetrain (M_{YN} in Figure 4-2).	Hub, main shaft flange bolts, main shaft	Primarily driven by aerodynamic loads and therefore sensitive to annual TI distribution, shear, air density and wind speed distribution. It is also more sensitive to upflow angle than other load components.
Shaft torque (rainflow counts) (steel)	Torque load acting from the hub through the mainshaft (M_{XN} in Figure 4-2), translated into DEL using rainflow counting (distinct from following two load component calculations).	Hub, main shaft flange bolts, main shaft, planet carrier, gearbox housing, main frame	Primarily driven by aerodynamic lift forces and therefore sensitive to annual TI distribution and wind speed distribution. Time split between below and above rated operating time is a significant driver.
Bearings (torque duration, m=3)	Torque load carried through the gearbox (M_{XN} in Figure 4-2), translated into load duration distribution (LDD) using an m = 3 to represent bearing life.	Drivetrain bearings	LDD calculation driven by time at rated operation and number of rotations at a given load, thus primarily sensitive to wind speed distribution.
Gearing (torque duration, m=10)	Torque- load carried through the gearbox (M_{XN} in Figure 4-2), translated into LDD using an m = 10 to represent gearing life.	Drivetrain gears	
Yaw bearing, pitch moment (steel)	Bending moment acting between the mainframe and tower top through the yaw bearing (M_{YT} in Figure 4-3) also known as nodding moment.	Main bearing housing, gearbox housing, mainframe, yaw system, tower top (cans, welds and bolts)	Primarily driven by aerodynamic loads and therefore sensitive to annual TI distribution, air density and wind speed distribution. Less sensitive to shear because it is in the fixed frame where shear does not have a cyclic impact.
Yaw bearing, yaw moment (steel)	Bending moment acting between the mainframe and the tower top through the yaw system (M_{ZT} in Figure 4-3).	Main bearing housing, gearbox housing, mainframe, yaw system, tower top (cans, welds and bolts)	

Table 4-1 (continued)
Key load elements

Load Element	Description	Turbine Components	Fatigue Load Driver
Tower base bending, lateral (steel)	Bending moment acting on the tower base (M_{XT} in Figure 4-3, but at the turbine base) also known as side-to-side moment.	Tower (cans, welds and bolts), foundations	Primarily driven by aerodynamic loads and therefore sensitive to annual TI distribution, air density and wind speed distribution. Less sensitive to shear because cyclic lateral moments are driven by torque. Lateral bending is not commonly the design driver for the tower (longitudinal loads are typically much higher).
Tower base bending, longitudinal (steel)	Bending moment acting on the tower base (M_{YT} in Figure 4-3, but at the turbine base) also known as fore-aft moment.	Tower (cans, welds and bolts), foundation	Primarily driven by aerodynamic loads and therefore sensitive to annual TI distribution, air density, and wind speed distribution. Less sensitive to shear because the longitudinal load is driven by the thrust force; this remains constant with constant shear.

Exact sensitivities and relationships between inflow conditions and loads are complex and in general cannot be simplified to equations.

General Approach to Site Life Assessment

If designed to the IEC standard [11], then design for fatigue is performed by simulating the fatigue loading expected from the design environmental and operating conditions. There are five design load cases (DLC) to consider for fatigue loading: DLC 1.2: power production with a normal turbulence model and wind speeds between cut in and cut out wind speeds; DLC 2.5: power production plus the occurrence of a fault with a normal turbulence model and wind speeds between cut in and cut out wind speeds; DLC 3.1 and DLC 4.1: start-up and shut-down with a normal wind profile and wind speeds between cut in and cut out wind speeds; and DLC 6.4: parked (still or idling) with a normal turbulence model and wind speeds below 70% of the reference wind speed for a given turbine class. These fatigue load cases are used to develop the basis for the design loads for all structural components.

The loads results of these fatigue DLCs are lifetime cumulative fatigue loads obtained by counting the number of cycles at each stress level for a given time series of simulations, and extrapolating that to the design lifetime of cycles. The resultant value is called a lifetime DEL.

In order to calculate the site specific life, the same process of simulation and cycle counting is performed but using the site environmental and operational conditions instead. [15] notes that transient loads during start up and shut down may be large contributors to total damage and should be considered, although this reference is dated and the normal transient loading of modern turbines is a small contributor to overall fatigue loading. The site load (DEL) can be compared to the design load (DEL) to get a site load ratio. The fatigue site life can be calculated using Miner's rule:

$$Site\ life = Design\ life\ *\ \frac{Site\ load}{Design\ load}^{-m}$$

where the exponent "m" is the Wohler exponent, as described earlier in Section 5. For blades the Wohler exponent will be between 9 and 15, with the higher end of the range for carbon fiber, and steel components 3 or 4.

Inspections are very valuable for validating assessments and for providing feedback about the current condition of the component of interest. There are many non-destructive inspection techniques employed by other industries, some have clear applicability to wind turbine inspections:

- **Visual inspections**. Either assisted (telephoto lens or microscope) or unassisted close visual inspection can be used on all accessible components. The probability of detection of cracks and other damage for this method is the lowest of the types listed here.

- **Ultrasonic inspections**. High frequency sound waves are used to detect defects inside or on the surface of a material. This is a common tool for quality assurance in manufacturing.
- **Dye penetrant inspections**. This method uses a liquid dye to reveal and emphasize cracks that have broken the surface. It is best for small areas, perhaps which are already suspected of damage.
- **Magnetic particle inspections**. This method can detect cracks at or very near the surface through use of fine iron particles spread over the area of interest, which will concentrate around a crack. It is also best for small areas.
- **Thermography**. An infrared camera is used to map the heat radiated by the surface of a structure; this is currently employed for blades, and is performed while the turbine is operating, eliminating the need to have the turbine offline.

Rotors: Blades, Hubs, and Blade and Hub Connections

Blades can be made from a multitude of materials, commonly shells are made from fiberglass material with a foam core, while the structural spar can be wood, composite, carbon, or a combination. [15] describes the typical construction of a blade: "The blade profile is a hollow profile usually formed by two shell structures glued together, one upper shell on the suction side, and one lower shell on the pressure side. To make the blade sufficiently strong and stiff, so-called webs are glued onto the shells in the interior of the blade, thus forming a boxlike structure and cross section."

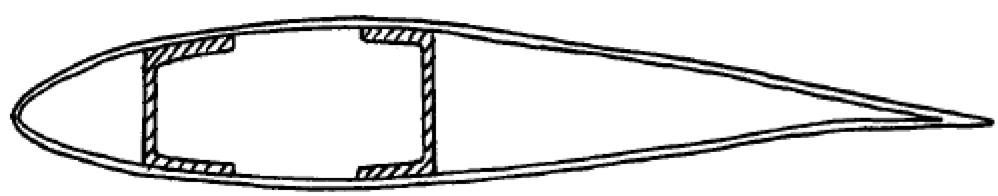


Figure 4-4
Blade cross section showing blade shells and two shear webs [15]

The approach outlined in "General approach to site life" above is used for blades. Design DELs are calculated along the entire length of the blade for all six load components shown in Figure 4-1. The approach can overestimate blade life because the only failure mode considered is failure due to high cycle fatigue. Blades can also fail due to extreme loads in bending or buckling, tower strike, environmental deterioration, lightning strikes, or manufacturing or design defects. The understanding of blade failure modes has improved in recent years but blades continue to grow in size at the same time introducing issues due to scaling effects not present in historical experience.

Inspections of blades are commonly done throughout the life of the turbine on a regular basis through visual inspection: ground based with telephoto lens camera, or a close visual inspection via rope access. Alternatives to visual inspection exist and include thermographic imagery, and ultrasonic.

Hubs are typically cast iron components. All three blades and the main shaft have connection points to the hub. The hub transmits the blade root moments and forces to the main shaft. The blade loads can be translated to the hub coordinate system (Figure 4-2) and cycle counted in a similar manner as with the blades. The resultant DEL is compared between design and site loading and site life calculated the same as for blades, but using a Wohler exponent for cast iron and considering just the blade root (edge and flapwise) load elements. Figure 4-5 shows a sketch of a hub.

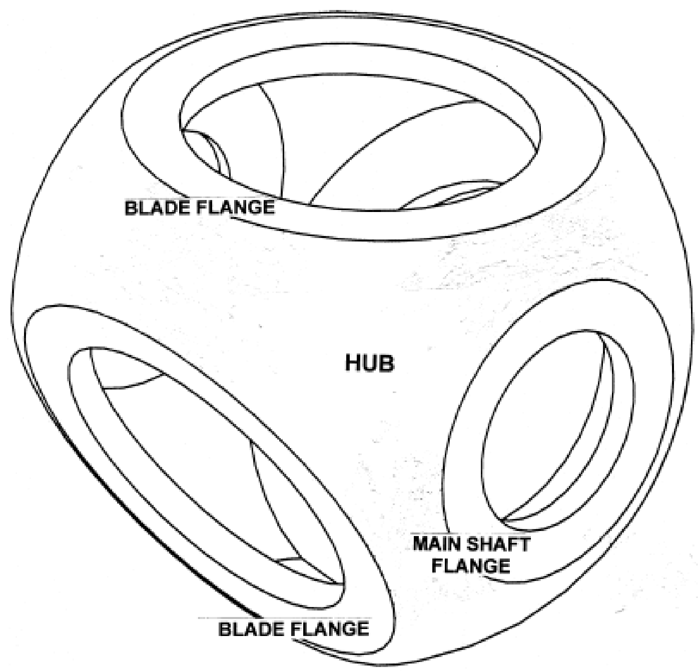


Figure 4-5
Schematic of wind turbine hub [15]

Hubs may be inspected visually or through non-destructive testing (NDT) methods: ultrasonic, magnetic particle, and so on.

Hubs may also fail before they reach the end of their fatigue life due to other failure modes such as extreme loads, manufacturing defects, or design defects. Bolted connections between blades and hub or main shaft and hub are also subject to fatigue loading and can fail due to poor maintenance practices (bolt tensioning sequence and method, torque applied, and so on). The primary concern with bolts is that the pre-tension (compression of mating surfaces) is maintained so that load is actually carried through reduction in the mating surface compression rather than additional bolt tension.

Drivetrain Components: Main Shafts, Main Bearings, and Gearboxes

The main shaft transmits rotational power (torque and speed) from the hub to the gearbox or directly to the generator and transmits non-torsional loads to the fixed system in the nacelle (main frame). When calculating RUL or site life, the approach ("General approach to site life") is the same as for hubs, taking into account how the loads from the hub transfer through to the main shaft. Main shafts can also fail due to extreme loading exceeding ultimate strength, manufacturing defects, or design defects. There has been some experience with fretting corrosion induced cracking in main shafts, the initiation occurring in the high contact stress area where the shaft contacts the main bearing inner race collar.

Main bearings support the main shaft and transmit non-torsional loads through the bearing housing to the mainframe. Many bearings are designed to a 20-year life based on the "L10" concept: of a large population of said bearings, 90% will reach the designated design life. This results in a mean time between failures (MTBF) of about five times the calculated L10 life. Bearings may end up with a shorter MTBF than design if the loads are higher, or, more commonly, due to poor maintenance practices, or defects in design or manufacturing. Main bearings are typically not included in structural analyses, and instead the expected site life is calculated based on historical failure rates from similar bearing designs, ideally from the wind farm of interest.

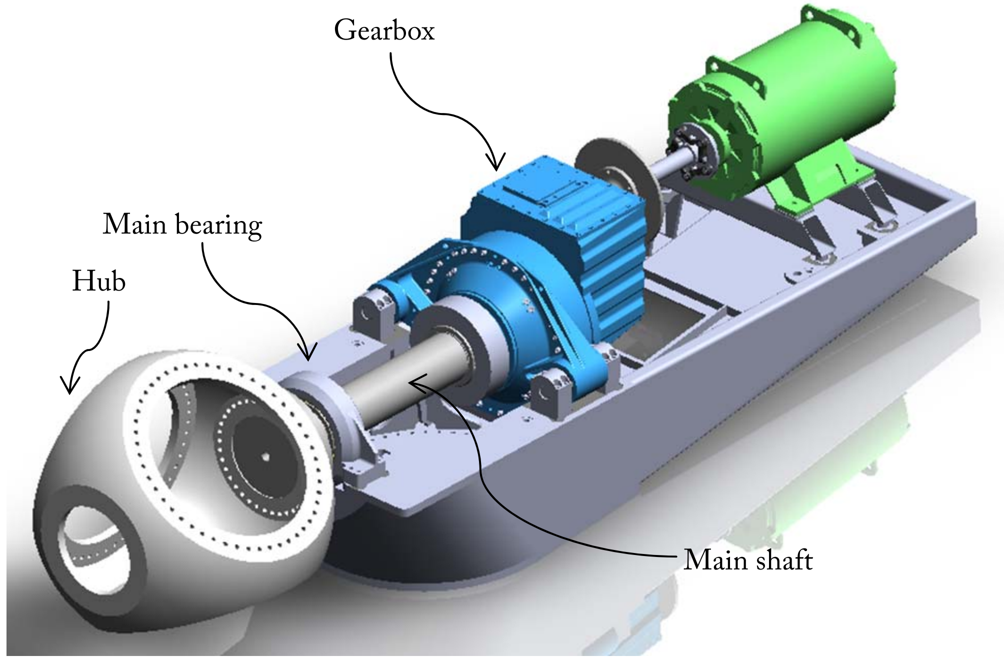


Figure 4-6
Schematic of typical drivetrain layout

Main bearing housings and gearbox housings (for three point designs) are considered to be in the structural load path. The load elements contributing to fatigue damage (and consuming fatigue life) include shaft thrust, pitch and yaw moments and shaft torque. The housings are evaluated in the tower static coordinate system (Figure 4-3).

Gearboxes are intended to reduce torque and increase speed and transmit rotational energy from the main shaft to the generator. Due to the complexity of the design details, the failure modes are not covered by this report. A RUL can include an assessment of site and design torque duration loading to understand the gear tooth (m=10) and gearbox bearing (m=3) fatigue damage accumulation. However, other failure modes with shorter MTBF than the high cycle fatigue load failure mode may cause failure first.

Main bearings and gearboxes can be inspected through borescoping. Housings can be inspected visually or through NDT methods: ultrasonic, magnetic particle, and so on.

Towers

Modern wind turbines are typically constructed with steel tubular towers, comprising multiple welded conical sections, joined together with bolted flanges (Figure 4-7). Structurally sensitive areas include welds, flanges, bolts, and particularly door areas. Towers may be inspected visually or through NDT methods: ultrasonic, magnetic particle, and so on. If the hot spots are known, then a limited number of welds will require inspections. Anchor bolts can only be inspected externally.

Figure 4-7
Partially constructed wind turbine tower

Tower site life can be calculated using the approach outlined in "General approach to site life" above, where the loads of relevance are yaw moment, yaw bearing pitch moment, and tower base longitudinal and lateral loads. Towers can also fail from extreme loads, which could be caused by an extreme wind gust, or operational error leading to overspeed or from a blade striking the tower. These are rare events and generally not modeled, except for extreme wind gusts which can be modeled probabilistically and have the same chance of occurring in any given year.

Foundations (Onshore)

Many variants exist for wind turbine foundations. The most widespread and mature foundation type is a spread footing. The spread footing design relies on vertical bearing at a shallow depth, typically around 3 m, and soil overburden to resist overturning. Piles may be used to transmit bearing loads down into higher strength materials deeper below the surface when soil properties near the surface are insufficient for demand. Foundations can be anchored directly into rock in locations with high quality rock. In rock anchor foundations, direct bearing on the rock coupled with tension in anchors is used to resist overturning. Many other foundation types exist, but are less common. In nearly all cases the foundations are site constructed of rebar, concrete, and high strength grout.

The tower is connected to the foundation pedestal through either high strength anchor rods or a foundation mounting part. Anchor rods are connected to an embedded steel ring in the foundation to resist uplift of the turbine tower. The loads from the anchor rods or the foundation mounting part are transmitted into the soil or rock through a reinforced concrete mass that constitutes the rest of the constructed foundation. The structural load path in the concrete is dependent on the foundation type.

Each piece of the structural load path is evaluated in the RUL assessment. These areas include: tower base flange grout; tower pedestal concrete in bearing and bursting; pedestal to foundation base connection; foundation base shear; foundation base bending; soil cyclic degradation; pile fatigue; and rock anchor fatigue. Additional areas of concern may exist in less common foundations and are to be specifically evaluated.

Information related to RUL assessment and discussion of issues for onshore is available in [16].

Foundations are challenging to inspect because of access. Anchor bolts are tested using "ping" tests, where they are struck and the pitch of the response is used as an indicator for tension. Loss of tension could be due to vibration loosening nuts, fracture, or corrosion.

Foundations and Support Structures (Offshore – Bottom Fixed)

Many variants exist for offshore wind turbine foundations. The most widespread offshore foundation consists of a single monopile driven into the seafloor. Multi legged jackets connected through smaller piles are typically used in deeper waters. In shallow waters gravity based structures can be used. All these technologies closely resemble foundation technologies developed for other offshore applications and the RUL assessment of offshore foundations for wind turbines will largely follow the existing best practices for similar portions of the foundation. Both loading from the turbine and wave loading must be considered in assessment of RUL.

Monopiles typically use a transition piece between the driven monopile and the tower. This is often connected through grouting the annulus between the monopile and the transition piece. This connection transmits significant bending loads between the transition piece and the monopile. These bending loads are atypical of other offshore grouted connections and require consideration specific to offshore wind turbines in assessment of RUL.

General (Repair-Ability, Corrosion, Bolts, Risk Assessment)

Some structural components can be repaired when damage is found, often returning the component back to its original condition. This is especially true for fiberglass damage and damage to welds. Fiberglass damage can be removed and often field repaired. Cracks in welds can be ground out and rewelded. It is also possible to arrest crack growth in a weld by drilling a hole at the ends of the crack. Cast iron components, like hubs, cannot be repaired, and must be replaced. Retrofits have been performed on wind turbine structural components in the past, and could be an option in some cases; examples include welding or bolting stiffener plates to an area with insufficient strength to redirect the load through the added plate.

Corrosion and other forms of environmental degradation must be monitored for all structural components because it can weaken the component beyond the assumptions of the analysis.

Bolts, which can be tested with torque checks should be replaced if damage is found. All bolts should be inspected, rather than a sample.

From a risk assessment and health and safety perspective, the consequence of failure (potential for catastrophic failure) should be considered on a component and failure-mode basis. For example, a through crack of a blade may result in the loss of the blade, and the potential for it to be thrown from the turbine. This would be a high consequence failure mode, motivating more in depth analysis and more frequent inspections. On the other hand, many modes of failure of the pitch bearing will result in the turbine faulting, giving the operators an opportunity to discover the failure prior to any secondary damage or threats to health and safety occurring.

Section 5: RUL Prediction Models

As discussed in Section 2, the analytical assessment consists of a calculation to evaluate the fatigue life of the turbine structural components; modeling is most commonly physics-based but alternative approaches exist including stochastic models, data-driven/artificial intelligence (AI) models, and combined models [8, 9]. These are discussed here.

Physics-Based Models

The most common modeling approach for both design and RUL estimation in the wind industry currently is physics-based. Physics-based models typically use an understanding of the failure mode and failure process to calculate how the system's states, in a particular situation (a specific site, with a specific turbine model), propagate through the model to failure. That understanding of the failure mode or process is typically gained through a combination of physical theory and experimentation and observation of similar engineered parts under similar situations. Challenges in using physics-based models include:

- Accounting for all factors influencing a failure mode; for example, material properties tested in a lab under controlled conditions may vary in the field under different temperature gradients, different specific loading time series, different salinity, and so on.
- Variability in manufacturing leading to a distribution of geometric and material properties around nominal values.
- Physical models must be validated based on experimentation and observation; some failure modes have not been studied in enough depth or with enough samples to develop accurate models. For example, environmental degradation of composite material in blades is a known failure mode, and while it is an area of current research, models to predict the rate at which a blade will experience degradation in a given environment are still not accurate enough to use for RUL estimation.
- Physics-based models require accurate, measured inputs. This can be challenging for wind farms, for example, an aeroelastic simulation of a wind turbine would require an accurate measurement of inflow including shear across the rotor plane in order to accurately estimate blade loads. Some wind farms measure shear at one or a limited number of locations across the project area, but it is highly unusual to have accurate shear estimates upstream of any given wind turbine.

A few strengths of physics-based models include:

- Models can be applied coarsely on a system level; however, at a lower accuracy because of the idealization of behavior, or they can be applied on a fine scale after breaking a system down into elements. The latter is exemplified by finite element models or multi-body system models. Applying models to smaller elements typically greatly increases the accuracy of the model at the expense of computational effort.
- Calibration to physical observations is easier because we have access to various intermediate states of the model. For example, if we associate "failure" of a tower due to a crack of a certain, predicted size, and upon inspecting the tower, found no crack of that size, then we can update the assumptions in the crack growth model to reflect the reality found in the field.

The most common physics-based model used for RUL assessment describes the fatigue damage accumulation of a material. A common example is described below:

When material samples are tested in a laboratory environment for fatigue strength, they are cyclically loaded at constant amplitude until failure. The results of these tests are combined to produce fatigue strength curves (also referred to as "S-N curves") such as the one shown in Figure 5-1. These curves are design detail and material-specific and the inverse slope of the log of the curve, often referred to as the "Wohler exponent," is designated by the symbol m. Common values for m are in the range of 4 for steel and 10 for fiberglass composites. Miner's rule is the mathematical equation used to sum fatigue damage from a number of random cycles at different load levels.

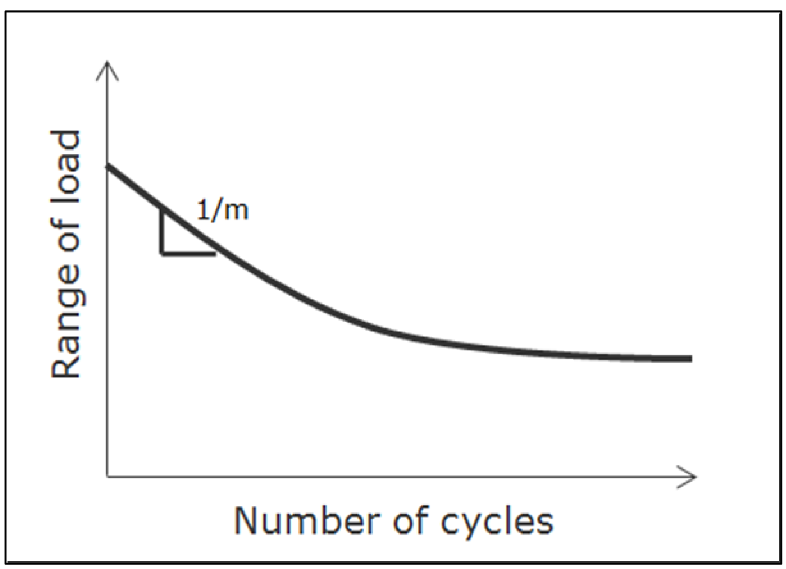


Figure 5-1
Example fatigue strength curve

Wind turbines experience highly variable loads due to the stochastic nature of winds combined with gravity, inertial, and other effects. Rainflow counting is a technique used to translate a highly variable load time series into an equivalent number of cycles at specified amplitudes. Once rainflow counting is done, Miner's rule can be applied to calculate DEL range, abbreviated R_{eq}. In the below equation, N_{eq} is the equivalent number of cycles (arbitrary but typically 10^7 for 20-year life), m is the slope of the material fatigue curve (S-N curve), and n_i is the number of expected lifetime cycles (over a given number of years) at load range R_i.

$$R_{eq} = \left[\frac{\sum (n_i R_i^m)}{N_{eq}} \right]^{(1/m)}$$

This can then be used in a limit state function which describes the limit (G) between the state of failure (G<0) and non-failure (G>0), where R_{allow} represents the material fatigue strength and x_i represent variables influencing the load and strength:

$$G(x_i) = R_{allow}(x_i) - R_{eq}(x_i)$$

A second type of physics based model is based on fracture mechanics. This model can be paired with the S-N approach described above, by switching over to a fracture mechanics model to calculate the time to failure once a crack has been detected and measured.

Stochastic Models

Stochastic models are built on probabilities of events. Purely stochastic models build relationships between two sets of data (inputs and outputs) without knowledge of the physical phenomenon behind the relationships. An example is called an "aggregate reliability function," which is developed by modeling aggregated failure data using a probability density function (exponential, normal, lognormal, Weibull, and so on). However, stochastic models and physical models are often combined.

Challenges associated with stochastic models include:

- A substantial amount of input and output data is required to obtain a good model. This may be feasible with replaceable components, like gearboxes. But for structural components such as the tower, there is not a lot of data on failures so developing stochastic models is not currently an option.
- Without some kind of physical model, the selection of input data and model input assumption is arbitrary and may take some trial and error to define well.
- Expert judgment may be required to determine which cases are appropriate applications for a given stochastic model.
- They are usually not good at extrapolation, so they can only be applied for limited situations from which they were "trained."

Strengths of stochastic models include:

- Statistical information about the results is readily obtained, such as uncertainty distributions and confidence intervals.
- Methods exist to combine expert judgment, physical models, and stochastic models.

A classic example of a stochastic model used for life estimation is a Weibull distribution fit to failure data for gearboxes. It is a time-based failure rate estimation that often will provide a good fit for observed failures in the field. Various regression methods exist to fit a distribution to data, some can be used without a significant amount of data; there are well established methods for evaluating the goodness of the fit. Figure 5-2 shows how different failure modes combine to yield a classic bathtub curve of failure rates. Both the early infant mortality failure and the wear out failure curves can be fit to Weibull distributions.

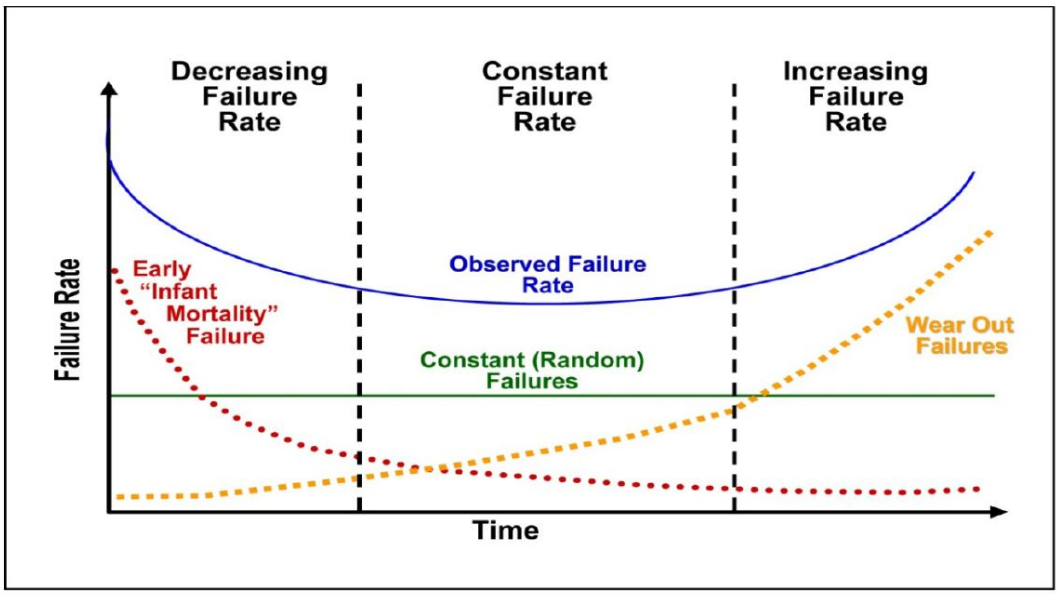


Figure 5-2
Bathtub failure rate curve

When too many failure modes are aggregated into the dataset, the stochastic approach is less appropriate.

An example of a combined stochastic and physical model is applying probabilistic methods to the fatigue limit state example shown above. The variables (x_i) influencing G are uncertain and can be represented stochastically. When this is done, mathematical techniques (such as first order and second order reliability methods (FORM and SORM)) can be applied to calculate the probability of failure (where G<0). This is a common approach taken with structural components that do not have a track record of failures from which to use statistical fitting alone to predict failure. It can also be updated with field observations, becoming more accurate as more information becomes available.

Stochastic models require a significant sample size of failure data, ideally for each failure mode under consideration.

There are stochastic models that are more complex than aggregate reliability functions, such as static or dynamic Bayesian networks. These require relational understanding in terms of probabilities of the system variables. It is attractive because it can be developed with incomplete datasets. This type of model does not provide a calculated RUL value, but can provide binned RULs (<1 month, <5 years, and so on) [16].

Data-Driven and Artificial Intelligence Models

Data driven or AI models depend on a large set of data to develop intelligent system models through learning and training. They are useful for very complex systems and can utilize noisy data; physical understanding of the failure process is not needed. Though wind turbines are not currently heavily instrumented structures, the recent advances in sensor technology will likely lead to more cost-effective sensors and thus more available data on an ongoing basis from which to support data-driven health monitoring [16].

Challenges with data-driven/AI models include:

- While some information can be gleaned if the training data do not include failures, the RUL cannot be estimated without a significant amount of data that includes failures. These data are not yet available for most wind turbine structural components.
- These models are most appropriate for short-term predictions, which is more applicable to predictive maintenance rather than RUL estimation.

Artificial neural networks (ANN) are one type of AI that could be used for fault diagnosis and online fatigue monitoring, though the latter application is still under development [9]. ANNs are comprised of a number of nodes connected through synaptic weights, which are tuned or trained through training datasets.

Though data-driven models are unlikely to be of use for wind turbine RUL estimation due to the lack of a significant amount of failure data for each structural component, some data-driven approaches, such as ANN, can be helpful in combination with physical models. [16] describes using ANN for parameter estimation in combination with a physical model where there are some unmeasurable parameters. This may be relevant for wind turbines where physical models require some assumption of certain unmeasured or highly uncertain quantities such as shear at each turbine location.

Prediction Models Conclusions

The different approaches to modeling RUL have strengths and weaknesses. In general, the intense data requirements for data-driven approaches will make these models unusable for most wind turbine structural failure modes for some time. However, in the meantime, they may have some applicability in estimating parameters that feed into physical models. Physical models can be developed with less data, but require complete knowledge of the mechanics of failure and require domain expert involvement in tuning models as more information and data becomes available [16]. Additionally, data-driven and stochastic approaches may show applicability to non-structural component failures, though that is outside the scope of this study.

Section 6: Strategies for Reducing Model Uncertainty

When using any model or inspections to predict RUL, there is uncertainty associated with the estimate. In this section we discuss the sources of uncertainty and steps that can be taken to reduce uncertainty.

Uncertainty can be categorized into the following groups:

- **Aleatoric uncertainty**. irreducible uncertainty due to the inherent random nature of an underlying physical process (for example, the 1 in 50-year gust wind speed at a certain location)
- **Epistemic uncertainty**. a lack of knowledge on the part of the designer and is therefore in principle reducible with the application of better, or more complete, knowledge of a given system (for example, the fabricated mass of a hub)

Sources of Uncertainty

The sources of epistemic uncertainty contributing to the overall uncertainty in a life estimate using the physics-based model of Miner's rule (see Section 5) include uncertainty in the inflow conditions for any particular turbine, modeling uncertainties, and uncertainties in material properties:

- Inflow conditions uncertainty
  - Wind speed and direction distribution
  - Turbulence distribution
  - Wind shear distribution
  - Air density
  - Up-flow angle
  - Un-modeled parameters such as veer, correlations between inflow conditions, wakes, and so on
- Modeling simplifications and uncertainties
  - Aerodynamics
  - Structural dynamics
  - Damping

- Actuator models
- Electrical and control systems
- Turbulence models
- Corrosion, solar degradation, or other un-modeled degradation mechanisms

▪ Operating conditions uncertainties
  - Downtime/operating state
  - Starts and stops
  - Off-yaw operation
  - Wind sector management
  - Controller parameters

▪ Material properties
  - S-N curve (fatigue strength)
  - Miner's rule (simplified model of fatigue damage accumulation)

Uncertainty Reduction

Owners have the ability to impact many of the uncertainties listed above through on-site environmental conditions measurement campaigns, developing advanced monitoring and inspections plans, and through load measurement. These are detailed below.

On-Site Measurement

On-site measurement of environmental and operating conditions can be directly leveraged in site life estimates to reduce uncertainty in estimated inflow conditions and operating conditions.

Met tower data are valuable from pre-construction periods because they provide a basis for the undisturbed wind flow at the project. Pre-construction data are most valuable for high accuracy life assessments if they have the following qualities:

▪ Multiple years of consistent data collection, with well-maintained and calibrated sensors.

▪ Multiple met towers well distributed over the site, with at least one met tower in each type of terrain (for example, if some turbines will be sited in a forest and others in an open field, there should be at least one met tower sited in the forest and at least one in an open field; likewise if there are some turbines on the edge of a mesa and some well back from the edge on flat ground, met towers should be collecting the spectrum of inflows here as well).

▪ Wind speed, shear, air pressure, temperature, and upflow angle should all be collected and saved in 10-minute statistics (mean, standard deviation, maximum, and minimum).

- Unusual weather events should be investigated. For example, if the TI at 18 m/s is usually around 8-10%, and there is one storm where it is 30%, that event should be investigated to understand how frequently it occurs.
- Long-term correlation and adjustments should be applied as necessary.
- Any modifications made to the measurement system should be well documented.

Met tower data are also valuable from the operation period (often referred to as "permanent met towers"). Permanent met towers are often hub height and are most valuable for high accuracy life assessments if they have the following qualities:

- Located in a representative site but also unwaked in some directions
- Utilizing well maintained, calibrated sensors
- Wind speed, shear, air pressure, temperature and upflow angle should all be collected and saved in 10-minute statistics (mean, standard deviation, maximum, and minimum).
- Any modifications made to the measurement system should be well documented.

SCADA data and other operating data that track the project operating conditions can also contribute to reducing uncertainty, especially if they have the following qualities:

- Tracks on a turbine-by-turbine basis turbine status, wind speed, rotor speed, blade pitch, power, nacelle orientation, yaw error (mean and standard deviation at minimum), downtime, starts/stops
- Synchronized with maintenance data, failure data, repair/replacement data
- Downtime, starts/stops
- Modifications to control systems and control parameters

Record keeping is an important part of leveraging site data. There are benefits to having an integrated dataset in a central database. This would ideally include synchronized data from all wind turbines from project initiation through current, as well as all permanent met data, any remote sensing data collected, as well as failure data, fault data, and other important maintenance records. This type of central database does not inherently reduce uncertainty but it greatly increases the chances that the whole picture of the project's operations is understood, data are available and comprehensive and synchronized.

Advanced Monitoring and Inspections

SHM is a field of online monitoring applied to structures to attempt to identify structural issues early such that they can be optimally scheduled, which is of high value to offshore wind projects. Further, it can be a powerful risk mitigation strategy for life extension. An uncertain life assessment can be used to inform decisions about investments in SHM, which complements the life assessment by mitigating risks of catastrophic failure. This is also true of structural inspections in general. SHM can be thought of as serving the same purpose as a structural inspection, but having the benefit of providing information on the structural health continuously instead of discretely like inspections [17].

SHM and structural inspections have the objective of localizing any damage, quantifying the extent of the damage, and if possible, providing information about the propagation of the damage [18].

If detailed design information is available, comparative vacuum sensors could be considered [19]. They are used in the aircraft industry and work by creating a vacuum over a hot spot such that if any damage were initiated, the pressure in the sensor would change, and the user could be notified. It is likely uneconomical to use such sensors if the most likely areas to see damage first are not known.

The successful implementation of an SHM or inspection campaign depends on assessment of (1) probability of failure, (2) consequence of failure, and (3) probability of detecting damage.

Load Measurement

Load measurement campaigns can be used to help reduce the uncertainty in modelling by measuring loads on a specific turbine and correlating them to the measured inflow conditions. Though overall uncertainty is likely reduced through load measurement campaigns, there is new uncertainty introduced through the load measurement campaign itself.

Loads measurement campaigns are common for prototype turbines during the type certification process; however, information is typically proprietary to turbine OEMs. If this information is not available, for example, if a *detailed* design basis (as defined earlier) is not available, as described in Section 3, then a loads measurement campaign can assist in developing a turbine specific model, but it would be a significant undertaking which would also require developing a control code. With today's complicated control codes, this would be a significant undertaking. However, with earlier turbine models, system identification techniques may be sufficient to recreate a control approach.

Additional benefits of doing a loads measurement campaign are to identify the loading issues of a particular turbine which may be different from those modeled due to simplifications in modeling, or unknown/unmeasured particularities about a turbine such as the blade angle deviation, airfoil deviations, and unique cases of dynamic loading or existing damage that may redirect load patterns [20]. This would only be useful if the *detailed* design basis was available, and the loads measurement was being used to identify how a particular turbine behaved differently than it was originally modeled. The results would only be applicable to the turbine that the measurement campaign was applied to.

A full prototype loads measurement is outlined in Table 6-1 while a more reduced scale campaign is outlined in Table 6-2, which was trialed by [20] for the purpose of improving life assessments. The cost savings from a full prototype loads measurement campaign down to the reduced scale campaign would be a notable reduction if the period of measurement was limited to 3-4 weeks or less. The authors of [20] demonstrated an ability to measure loads using a limited loads campaign to understand the dynamic behavior of the instrumented turbine; however, they did not show the effort could be applied to other turbines of the same type, or extrapolated to periods before or after the measurement campaign. Without such capability, the benefit of doing loads measurement is very limited. However, they did not have access to TI data to use as a classification parameter. Had an accurate TI measurement been available, the loads measurement campaign would likely have been more fruitful.

Table 6-1
Type testing prototype load measurement campaign

Component	Sensors	Notes
Blades	Blade root flap bending Lead-lag bending	At least one blade
Rotor	Tilt moment Yaw moment Rotor torque	
Tower	Tower bottom bending (two directions)	
Turbine behavior	Electrical power, rotor speed, pitch angle, yaw position, rotor azimuth	Grid connection, brake status recommended
Meteorological	Wind speed, wind direction, air temperature, air density	Shear and temperature gradient recommended

Table 6-2
Reduced scale load measurement campaign per [20]

Component	Sensors	Notes
Tower	Tower top and tower bottom bending Acceleration in tower top and nacelle	Authors of [20] used 5 strain gauges and 5 accelerometers
Turbine behavior	Electrical power, azimuth, rotor speed	
Meteorological	Wind speed, wind direction, air pressure and temperature	

Another application of loads measurement and SHM (coupled with loads modeling) is to determine the impact of operational modifications like derating on component life, as was done in [17]; however, application is outside the scope of this paper so is not detailed here.

In the aircraft industry, the “flight leader” concept is common, where conclusions about structural integrity of some airplanes are drawn based on inspections results from the airplane with the most flights of a fleet. This concept could be applied to wind turbines such that a loads measurement campaign, monitoring or inspection campaign is applied to the turbine(s) with the highest loading, and the conclusions are applied to other turbines of the same design. This is an attractive concept in theory, but application is challenging for wind turbines because, in general, much less data are gathered on any individual turbine compared to airplanes. This means that once uncertainty is accounted for (1) it may not be clear which turbines are the flight leaders, (2) unaccounted for variables (like off-yaw operation or improperly implemented wind sector management) may lead to non-flight leaders having higher loads than flight leaders, (3) variability in material strength may lead to flight leaders showing damage later than non-flight leaders, and other potential flaws with the flight leader concept. It still has potential to be useful for wind turbines, but needs to be implemented carefully and will be easier to implement in projects where more data are collected on the individual turbine level. Also, as the industry develops a greater understanding of correlations in strength and loading across a sampling of wind turbines or across a wind farm, the flight leader concept may prove a valuable tool.

Section 7: Cost Benefit Analysis

A cost model was developed to assess the impact of various approaches to life assessment on project operations. Some owners may wish to take a minimalistic approach, and generally rely on the design life of the turbine (Scenario A), others may wish to take a proactive approach to acquiring a low-uncertainty life assessment, using some of the techniques listed in Section 6 (Scenario B), and others may wish to take the most involved approach of performing a probabilistic assessment (Scenario C). Each of these scenarios has its own set of costs and benefits, which are explored in a probabilistic model developed for the purpose of comparing the scenarios against each other.

Scenarios and Model Inputs

In all scenarios it is assumed that the project stakeholders take a strategy to avoid catastrophic collapse (regardless of approach-- inspections, decommissioning, repairs, and so on), because catastrophic collapse has the following risks associated with it:

- Potential impacts to insurability, insurance premiums, and so on.
- Potential impacts to turbine availability if local jurisdictions, landowners, and so on, force the project or part of the project to shut down after a collapse for safety reasons.
- Potential impacts to the stakeholder public relations, impacting ability to pursue other project development endeavors or operations at other projects.
- Potential failure to meet contractual obligations for energy delivery.

The risk of structural failure implied by the design standards is somewhat low, and there is potential that the structural components will survive longer than the nominal calculated life. However, risks taken by wind farm owners should be generally in line with the design standards as they have been developed through broad industry consensus and are in line with acceptable risk of failure for other structures with similar consequence of failure and similar value to society.

All scenarios assume the base project parameters listed in Table 7-1. Most parameters are based on assumptions of the model and thus are deterministic.

Table 7-1
Cost model common parameter values

Parameter	Value	Units	Uncertainty Modeling
Number of turbines	99	Turbines	Deterministic
Turbine capacity	2.0	MW	Deterministic
Design life	20	Years	Deterministic
Operating life objective	30	Years	All scenarios aim for 30 year life but Scenario A comes short (see Appendix D for details)
Structural inspection cost (towers)	$6,000	Cost per turbine per inspection	Normally distributed with an uncertainty of $1,500
True site load margin on towers, blades, hubs and mainframes	-8% to 8% uniformly distributed across turbines (mean margin across turbines = 0%)	Margin between site load and design load	Deterministic (described in more detail below)
Foundations and remaining structural components site life	30	Years	
Power purchase price	$50	Price per MWh	Deterministic
Net capacity factor	38%	N/A	Normally distributed with standard deviation of 2%
O&M costs	$53,600[2]	Cost per turbine per year	Normally distributed with standard deviation of 15%
Soft costs[1]	$29,000	Cost per year	Deterministic
Discount rate	7%	N/A	Deterministic
Inflation rate	2.5%	N/A	Deterministic

[1] Soft costs comprise property tax, administrative, financial, and legal costs, insurance, and fixed land lease costs.
[2] This represents the 20-year average; implemented such that each year varies based on expected failure rates.

Scenario A embodies a minimal approach to life extension, where the project owners take some simple steps to understand the site environmental conditions relative to the design conditions, and generally understand them to be roughly equivalent. The turbines are designed for 20 years, they are operated for 20 years and then, because the exact risk is unknown, an intensive inspection campaign is undertaken annually to reduce uncertainty and avoid catastrophic failure. Further, because little was done to understand or prepare for the fatigue driven failures, when some structural components fail prior to the end of the operating life of 30 years (such as blades, hubs, mainframes), replacement parts are difficult to get and some turbines are decommissioned. The additional inputs to Scenario A are detailed in Table 7-2.

Table 7-2
Cost model Scenario A parameter values

Parameter	Value	Units	Uncertainty Modeling
Inspection plan	All towers every year starting year 20	N/A	Stochastic
Decommissioning rate due to blade, hub, mainframe failures[1]	1%	Percent of turbines decommissioned each year in years 21-30	Log normal with standard deviation of 0.5%
Uncertainty in life assessment	High	N/A	N/A
Change in O&M costs	No change	N/A	N/A

[1] A high level analysis was performed, looking at the most likely failure rate for blades, hub, and mainframe failures given the assumed load margins, number of turbines, and assumed design probability of failure to estimate a realistic number of failures, though there is still uncertainty in this estimate.

Scenario B embodies a relatively proactive approach to life extension: an intentional campaign is undertaken to understand the site life as accurately as possible. This involves (1) an extensive light detection and ranging (lidar) campaign to map the wind flow, including turbulence intensity, shear and wakes, across the site and (2) a detailed analysis of operating data to capture site specific details such as turbine specific downtime, start/stops, implementation of wind sector management, and so on. Though this comes at a cost, the benefits are that in this scenario, inspections can be targeted at some of the higher risk turbines, supply chain can be well planned to avoid decommissioning turbines due to parts that cannot be sourced, and contracts can be maintained out to 30 year terms with less risk of non-conformance on terms impacted by turbine life. The inputs to Scenario B are detailed in Table 7-3.

Table 7-3
Cost model Scenario B parameter values

Parameter	Value	Units	Uncertainty Modeling
Inspection plan	Half the towers with the highest risk starting year 20	N/A	Deterministic
Cost of lidar campaign	$500,000	One time cost in year 10	Normally distributed with uncertainty of $100,000
Cost of operating assessment	$100,000	One time cost in year 10	Normally distributed with uncertainty of $30,000
Uncertainty in life assessment	Moderate, not well understood	N/A	N/A
Change in O&M costs	Hub, blade, and mainframe replacements in 1% of turbines	Increase in failure rates due to hub and blade failures in years 21-30	Log normal with standard deviation of 0.5%

Scenario C entails a very engaged approach to life extension which involves a probabilistic approach to life assessment that can be leveraged in decisions about when to inspect and to what extent to inspect, as well as spare parts plans. If a full probabilistic approach is taken, including assessment and development of models for various failure modes, then in addition to the benefits experienced in Scenario B, under this scenario RBI can also be utilized. RBI is defined in Section Section 2: and detailed in Appendix C.

Table 7-4
Cost model Scenario C parameter values

Parameter	Value	Units	Uncertainty Modeling
Inspection plan	Risk based inspections[1]	N/A	Deterministic
Cost of uncertainty reduction (per Scenario B)	$600,000	One time cost in year 10	Normally distributed with uncertainty of $130,000
Cost of RBI analysis	$200,000	One time cost in year 10	Normally distributed with uncertainty of $60,000
Uncertainty in life assessment	Moderate, well understood	N/A	N/A
Change in O&M costs	Hub, blade, and mainframe replacements in 1% of turbines	Increase in failure rates due to hub and blade failures in years 21-30	Log normal with standard deviation of 0.5%

[1] RBI analysis shows inspections should be performed on a third of the turbines in year 20, 24 and 27.

Site Load Margin

Amongst the parameters listed in Table 7-1 includes the "true site load margin" for certain structural components: towers, hubs, blades and mainframes. This is a key assumption of the analysis because it drives decommissioning rate in Scenario A, and repair and replacement costs in Scenarios B and C. Site load margin is defined in Appendix A. It varies from site to site but it is not uncommon for the value to be between -10% and +20%.

The larger the site load margin, the longer the site specific operating life, as explained in Section 4. It is the combination of various inflow parameters relative to the design levels for those parameters that lead to the design margins at a given site. For example, take a site with TI of 14% and a design TI of 16%, if all other inflow conditions were equal, then there would be site load margins ranging from 1% to 14% across various structural components, depending on that components sensitivity to turbulence.

As described in the table, it was assumed that a third of the turbines have a site load margin of 8%, a third 0% and a third -8% such that the average across the project is 0%. Turbines with a positive site load margin are loaded more lightly than designed for and turbines with a negative site load margin are loaded more heavily than designed for. Both situations result in some elevated risk of failure within the 30 year life assumed, though the turbines with a larger site load margin have a lower risk than those with a smaller or negative margin. This risk was modeled using a log-normal distribution with a mean probability of failure of 1 in 1,000 in year 20, and increasing beyond that for zero load margin. For 8% load margin, the mean site life is about 25 years for steel components, so the model is tuned to show a risk of failure of 1 in 1,000 in 25 years for those turbines.

For the sake of simplicity, the probability of failure for the above structural components was modeled as constant in years 21-30, and results in approximately 1% of turbines experiencing a structural component failure every year between years 21 and 30.

Since all three scenarios are considering the same project specifics, with different approaches to life assessment and extension, the above described assumptions apply to all 3 scenarios with different results:

- Scenario A: approximately 1% of turbines are decommissioned each year when they experience failure of a structural component. This results in decommissioning of 10 turbines by year 30, lowering the revenue through electricity sales.
- Scenarios B and C: approximately 1% of turbines experience a structural failure every year and they are replaced so that no turbines need to be decommissioned in the 30 year life. The impact is to the annual average O&M costs (straight average across years 21-30):
  - Scenario A: $73,630 per turbine
  - Scenario B and C: $76,898 per turbine

Cost Benefit Analysis Results

The results of the analysis show that Scenario C is the most economically attractive in terms of both net present value (NPV) and internal rate of return (IRR), followed by Scenario B and then Scenario A. Scenario B's NPV is 25% higher than Scenario A. Scenario C's NPV is 31% higher than Scenario A. The IRRs are closer, with Scenarios B and C showing roughly 1% increase (calculated as a percent delta against Scenario A). The results are shown in Figure 7-1, Figure 7-2, and Table 7-5.

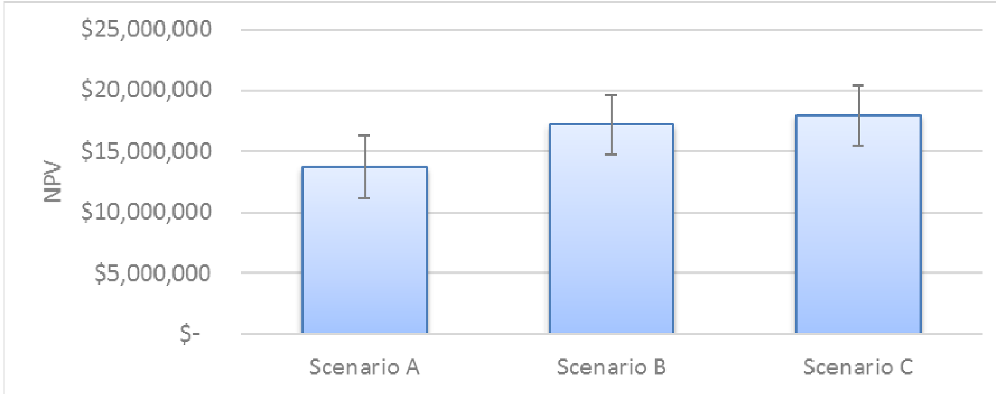


Figure 7-1
Cost Benefit Results: NPV

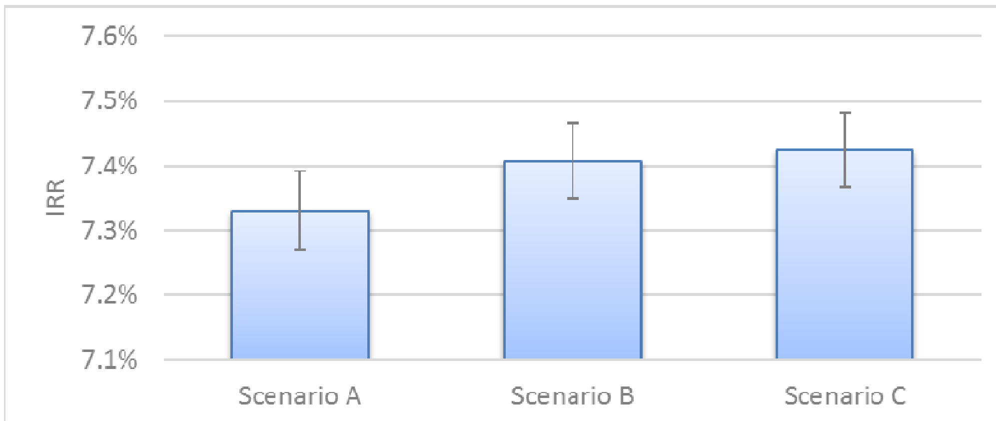


Figure 7-2
Cost Benefit Results: IRR

Table 7-5
Cost benefit results

Scenario	Mean NPV	St Dev NPV	Mean IRR	St Dev IRR
Scenario A	$13,703,488	$2,551,168	7.3%	0.1%
Scenario B	$17,169,383	$2,466,377	7.4%	0.1%
Scenario C	$17,929,650	$2,498,663	7.4%	0.1%

The uncertainty in the O&M costs is one of the primary drivers of uncertainty (shown as St dev in the table) in the NPV and IRR calculations—with over half of the uncertainty on NPV coming from O&M cost uncertainty. The decommissioning rate and inspection costs are influential factors for Scenario A's results; the assessment and lidar costs as well as the O&M costs are the most influential for both Scenario B and C. Inflation rate would also be a notable factor in all results, but was kept constant in order to focus on the technical aspects of the analysis.

Cost Benefit Discussion

The cost benefit analysis showed some of the benefits of investing in reducing uncertainty in life assessments:

- The benefit to reduced inspection costs (in Scenarios B and C, fewer of the turbines required inspections) due to having an ability to (1) identify the most heavily loaded turbines and (2) calculate optimal inspection intervals through RBI).
- The benefit of being able to inform a spare parts strategy to deal with increased failure rates of structural components prior to the decommissioning date of the project (Scenarios B and C both benefited from this while in Scenario A, turbines had to be decommissioned when irreparable structural damage was found because it was unexpected and thus no parts were available to be sourced)

However, in addition to the benefits illustrated by the cost benefit analysis, there are others that are harder to quantify; they include:

- Potentially better sale and loan terms in the case where a project with a planned extended life is involved. In the same way that a less certain energy estimate negatively impacts the terms of a loan, having more uncertainty about the life of the turbines may impact the terms of financing [21].
- One might also expect lower operating costs and less downtime in an extended life due to the ability to take a more proactive approach to life extension. Similar to how condition monitoring systems, if effective, can reduce the operating costs because more failures are caught early, having a proactive approach to life extension can also save costs.
- Higher confidence life assessments may also benefit a project through contractual terms: stakeholders may be more willing to sign long-term contracts, securing the financial picture for the project, if the uncertainty on life is lower.

These potential benefits and others have not been accounted for in the cost benefit analysis presented here but should be considered when looking at measures to reduce life assessment uncertainty.

Section 8: Recommendations for RUL Assessment Best Practice

Wind turbine life extension is most readily accomplished when a part of a holistic approach to wind farm management, that takes into consideration structural components through RUL assessment and strategies, inspections, non-structural component maintenance, contractual and environmental considerations, supply chain considerations, and EBoP considerations.

Best practices to optimize RUL assessment involve the following recommendations:

1. **Periodic updates to RUL assessment**.
    a. If project development depends on the successful planning and execution of an extended life, then a life assessment should be performed at project conception. It can be used to inform expectations for project availability, inspection costs and downtime, O&M costs, spare parts strategy, operating strategy, and so on. Otherwise, the first RUL assessment can be performed around year 10, to provide enough time to change operations (if required) early enough to impact the accumulated fatigue loading, and to develop the appropriate life extension strategy.
    b. Certain events would trigger a reassessment through the operating life, including: cracking or damage to any structural components, extended operations that impact loading (negatively or positively) such as incorrect wind sector management implementation, low availability, off-yaw operation, major storms, hurricanes, tornados, and so on, retrofits, and performance upgrades (particularly uprating).
    c. If no events trigger reassessment of RUL, then it can be performed at 5-year or more regular intervals.
    d. If the turbine OEM offers to perform an RUL assessment, they will be able to eliminate potentially conservative assumptions that a consultant would need to make of zero design margin. Especially at project conception, OEMs may be incentivized to provide optimistic life assessments. In which case, consultants can provide independent opinions.
2. **Certification**. In some jurisdictions, certification to extend the operations of wind turbines past their design lifetimes may be required. Various standards exist that can be used as the basis for life extension certification [6, 7].

3. **Life extension strategy updating**. At the same time as updating a RUL assessment, the strategy for life extension should be revisited.
4. **Record keeping**.

   To support accurate RUL assessment, the best practices described in Section 6 should be followed. Additionally, good record keeping is important.

   a. Centralized databases can be leveraged to save costs during RUL assessment. Maintaining all project records in a standard format and centralized database can significantly reduce the cost of manual data processing, formatting, and synchronizing. A key aspect of this is O&M historical records.

   b. O&M historical records should contain the history (dates and detailed scope) of key component replacements, key maintenance activities, upgrades, changes in operations such as uprates, derates, extended downtime, and so on.
5. Key measurements through monitoring and inspections.

Throughout an extended life, online monitoring and/or inspections may be appropriate. If implemented properly, the data from SHM, CMS, inspections, and so on, can be used to improve RUL estimates, and help support life extension strategies. Section 6 details potential benefits of these options and provides recommended best practices for their implementation.

Section 9: Conclusions

It can be challenging to estimate the RUL for wind turbines, as it is for any structure, but particularly for wind turbines because the industry has a minimal amount of experience with fatigue-related failure of structural components. Site specific RUL assessment is very dependent on inflow conditions and the turbine design conditions. Best practices involve assessing the relative loading from site conditions and design conditions, investing in measures to reduce uncertainty (such as operational data review and lidar/sodar measurement campaigns), as well as following recommended guidance on measurements and record keeping. A cost benefit analysis reported on in Section 7 showed a notable benefit to NPV for scenarios where an investment was made into reducing RUL assessment uncertainty, and where the benefits of that reduced uncertainty were leveraged to reduce inspection frequency, especially through RBI, and to plan strategically for structural component failure.

There are many different approaches to RUL estimation, all of which have their own benefits and drawbacks. The more advanced approaches (data-driven, AI-based, and so on) will not be largely viable until the wind industry has gathered more fatigue-driven structural failure data. In the meantime, physics-based models provide RUL estimations generally accurate enough for high level planning for extended operations.

Section 10: References, Bibliographies, and Index

References

1. Wiser, R., et. al. "Berkeley Lab study shows significant potential for further turbine scaling." Windpower Engineering and Development. Nov 28, 2016.
2. Global Wind Energy Outlook 2016. Global Wind Energy Council. October 2016.
3. Wiser, R., Bolinger, M. 2015 Wind Technologies Market Report. LBNL. August 2016.
4. U.S. Wind Industry Annual Market Report, Year Ending 2015. American Wind Energy Association. 2016.
5. Wind in power 2015 European statistics. The European Wind Energy Association. February 2016.
6. DNVGL-SE-0263 Certification of lifetime extension of wind turbines. March 2016.
7. DNVGL-ST-0262 Lifetime extension of wind turbines. March 2016.
8. ISO 2394 International Standard: General principles on reliability for structures. 2nd Ed. 1998.
9. Celle, N. Fatigue Load Monitoring with Standard Wind Turbine Signals. PhD Thesis. Universitat Stuttgart. April 2010.
10. Welte, T., Wang. K. Models for lifetime estimation: an overview with focus on applications to wind turbines. Advanced Manufacturing 2:79087. 2014.
11. International Electrotechnical Commission. (2008). Wind Turbines – Part 1: Design requirements. 61400-1 Third Edition 2005-08.
12. DNVGL-SE-0441 Type and component certification of wind turbines.
13. Fan, X., et. al. "A Particle-Filtering Approach for Remaining Useful Life Estimation of Wind Turbine Gearbox." International Conference on Chemical, Material and Food Engineering. CMFE-2015.
14. DNV GL "Technical Background to Extending Wind Turbine Operating Life." Document EAA-WP-06. Nov. 30, 2016.

15. DNV GL Guidelines for Design of Wind Turbines. DNV/Riso. Second Edition 2002.
16. Sikorska, J., et. al. “Prognostic modeling options for remaining useful life estimation by industry.” Mechanical Systems and Signal Processing Journal 25 (2011) pp. 1803-1863.
17. Griffith, T., et. al. “Structural Health and Prognostics Management for Offshore Wind Turbines: An Initial Roadmap.” Sandia National Laboratories. Sandia Report SAND20012-10109. December 2012.
18. Schedat, M., et. al. “Structural Health Monitoring concept to predict the remaining life of the wind turbine structure.” IEEE Domestic Use of Energy 2016 International Conference. 30-31 March 2016.
19. Wishaw M, Barton. “Comparative Vacuum Monitoring: a New Method of In-Situ Real Time Crack Detection and Monitoring.” Structural Monitoring Systems Ltd. www.smsystems.com.au. Accessed March 2017.
20. Melsheimer, M., et. al. “Practical Experiences from a Load Measurement Campaign for the Assessment of the Remaining Service Life of Wind Turbines.” DEWEK 2015.
21. Bailey, Bruce. “The Financial Impact of Wind Plant Uncertainty.” NAWEA Symposium. Aug 6, 2013.

Appendix A: Load Margin Definitions

No site will perfectly reflect the conditions prescribed by the design standard and thus the site-specific loads will differ from the design loads. The following definitions are helpful (though, we note, that these terms can be defined differently thus it is important to define with use):

- **Site load margin**. When turbines are sited conservatively, there is margin between the site loads and the design loads, referred to as "site load margin," which represents the relative difference of the loads imparted by the site conditions and the corresponding design load (per DLC). For example, if there is an 8% load margin on the mainshaft in fatigue bending, this implies that the loads imparted by the site conditions are 8% lower than the design loads. The equation defining site load margin is:

$$Site\ load\ margin = \ M_S = 1 - \frac{Site\ load}{Design\ load}$$

- **Site load exceedance**. Site load exceedance is sometimes used instead of site load margin as a different way to communicate the same observation. The equation defining site load exceedance is:

$$Site\ load\ exceedance = \frac{Site\ load}{Design\ load} - 1$$

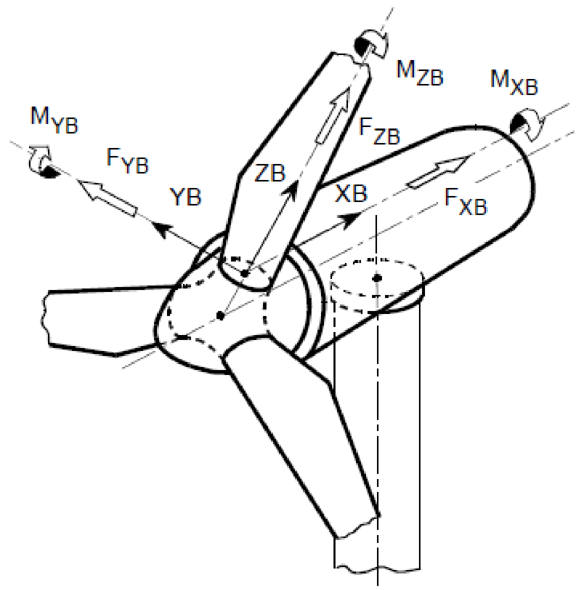
- **Design margin**. The design margin is a representation of the difference between the strength of the component (as designed) relative to the loads it is required to be designed to withstand (per design standards). The equation defining design margin is:

$$Design\ margin = M_D = 1 - \frac{Design\ load}{Design\ strength}$$

- **Total site margin**. There are instances where the site load exceeds the design load, but the component strength is still not exceeded because the design margin is large enough to compensate for the site load exceedance. This can be represented by the following equation where negative numbers mean that the component strength will be exceeded by the site loads (careful turbine siting avoids this), and the larger a positive number, the longer the component's site operating life (note, this applies to fatigue margins only):

$$Total\ site\ margin = \ M_S + M_D - M_S M_D$$

Appendix B: Turbine Coordinate Systems



XB in direction of the rotor axis

ZB radially

YB so that XB, YB, ZB rotate clockwise

Figure B-1
Blade load coordinate system

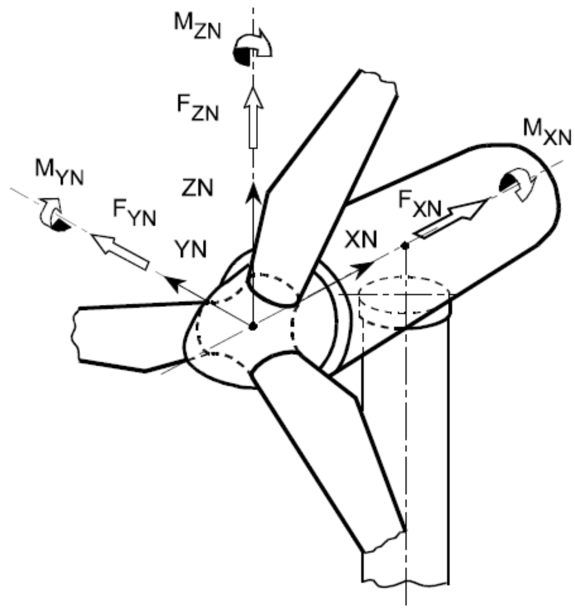


Figure B-2
Hub load coordinate system (coordinates rotate with rotor)

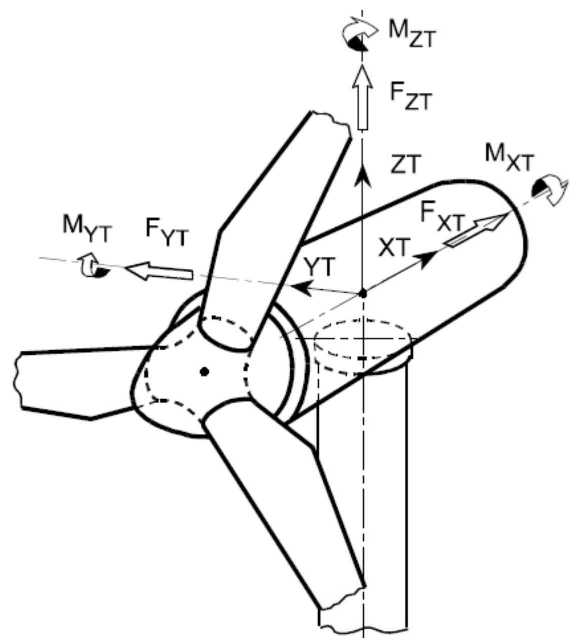


Figure B-3
Tower load coordinate system (coordinates are fixed)

Appendix C: Risk Based Inspections

At some point wind farm owners and stakeholders must consider options for end-of-life strategies, which include: (1) decommissioning even if there is remaining life in the structure, (2) continuing to operate blindly, or (3) something in the middle: taking steps to understand the risks, costs, and opportunities and making intentional, site-specific decisions to maximize returns while maintaining safe operation. To fully understand the condition of an asset, desktop analysis and field inspections must both be undertaken, as they will complement and inform each other.

RBI is a multi-faceted, optimized approach to life extension. It considers structural reliability analysis, inspection technology, detailed design / FEA, economics, and other aspects to develop life extension strategies that minimize the costs associated with life extension (where cost includes cost of O&M, structural repairs, inspection, analysis, downtime, and so on). The process includes analyzing project specifics to map out the following aspects:

- Risk of structural failure for each component as determined from models and data available to perform structural reliability analyses and model crack growth.
- Inspection technology available including its capability to detect damage early
- Costs associated with inspections, repairs, maintenance, and continued operation
- Target reliability levels (a reflection of stakeholder risk appetites)

From this mapping, intentional inspection plans can be developed in a qualitative or quantitative optimization (depending on data available) that will maintain risks below a target level by catching cracks before they are of a critical length, and thus allow for continued operation despite uncertainty in analytical approaches to predicting turbine operating life.

The concept involves combining an analytical assessment of the risk of failure with inspections that can be used to update that assessment with the additional knowledge gained from the inspection, whether that is damage found or not found. The classic example is to use crack growth modeling in combination with inspections for cracks. If the model predicts the probability of cracks of certain lengths, an inspection that discovers no cracks can potentially eliminate the probability of at least the largest cracks (those that the inspection technology can detect), allowing for a reduction in the risk.

Appendix D: Economic Analysis Details

Year	Number of Turbines			O&M Costs Per Turbine		
	Scenario A	Scenario B	Scenario C	Scenario A	Scenario B	Scenario C
1	99	99	99	-49,300	-49,300	-49,300
2	99	99	99	-43,400	-43,400	-43,400
3	99	99	99	-37,900	-37,900	-37,900
4	99	99	99	-32,700	-32,700	-32,700
5	99	99	99	-47,700	-47,700	-47,700
6	99	99	99	-35,800	-35,800	-35,800
7	99	99	99	-37,800	-37,800	-37,800
8	99	99	99	-40,300	-40,300	-40,300
9	99	99	99	-43,000	-43,000	-43,000
10	99	99	99	-66,700	-66,700	-66,700
11	99	99	99	-49,200	-49,200	-49,200
12	99	99	99	-52,100	-52,100	-52,100
13	99	99	99	-54,900	-54,900	-54,900
14	99	99	99	-57,500	-57,500	-57,500
15	99	99	99	-73,600	-73,600	-73,600
16	99	99	99	-62,400	-62,400	-62,400
17	99	99	99	-64,600	-64,600	-64,600
18	99	99	99	-66,300	-66,300	-66,300
19	99	99	99	-67,900	-67,900	-67,900

Year	Number of Turbines			O&M Costs Per Turbine		
	Scenario A	Scenario B	Scenario C	Scenario A	Scenario B	Scenario C
20	99	99	99	-89,900	-89,900	-89,900
21	98	99	99	-70,000	-73,268	-73,268
22	97	99	99	-70,900	-74,168	-74,168
23	96	99	99	-71,600	-74,868	-74,868
24	95	99	99	-72,000	-75,268	-75,268
25	94	99	99	-85,900	-89,168	-89,168
26	93	99	99	-72,500	-75,768	-75,768
27	92	99	99	-72,500	-75,768	-75,768
28	91	99	99	-72,600	-75,868	-75,868
29	90	99	99	-72,700	-75,968	-75,968
30	89	99	99	-75,600	-78,868	-78,868

The Electric Power Research Institute Inc., (EPRI, www.epri.com) conducts research and development relating to the generation, delivery and use of electricity for the benefit of the public. An independent, nonprofit organization, EPRI brings together its scientists and engineers as well as experts from academia and industry to help address challenges in electricity, including reliability, efficiency, affordability, health, safety and the environment. EPRI also provides technology, policy and economic analyses to drive long-range research and development planning, and supports research in emerging technologies. EPRI's members represent approximately 90 percent of the electricity generated and delivered in the United States, and international participation extends to more than 30 countries. EPRI's principal offices and laboratories are located in Palo Alto, Calif.; Charlotte, N.C.; Knoxville, Tenn.; and Lenox, Mass.

Together...Shaping the Future of Electricity

Program:

Renewable Generation

3002009997

Electric Power Research Institute
3420 Hillview Avenue, Palo Alto, California 94304-1338 • PO Box 10412, Palo Alto, California 94303-0813 USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com