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OF INTEREST TO THE FOLLOWING COMMITTEES:	
FUNCTIONS CONCERNED: ☐ EMC ☐ ENVIRONMENT ☐ QUALITY ASSURANCE ☐ SAFETY	

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TITLE:

Wind energy generation systems – Part 28: Through life management and life extension of wind power assets

PROPOSED STABILITY DATE: 2026

NOTE FROM TC/SC OFFICERS:

WIND ENERGY GENERATION SYSTEMS –

PART 28: THROUGH LIFE MANAGEMENT AND LIFE EXTENSION OF WIND POWER ASSETS

FOREWORD

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The text of this Technical Specification is based on the following documents:

DTS	Report on voting
88/XXX/DTS	88/XX/RVDTS

Full information on the voting for the approval of this Technical Specification can be found in the report on voting indicated in the above table.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

Mandatory information categories defined in this document are written in capital letters; optional information categories are written in bold letters.

The committee has decided that the contents of this publication will remain unchanged until the stability date indicated on the IEC website under "http://webstore.iec.ch" in the data related to the specific publication. At this date, the publication will be:

- reconfirmed,
- withdrawn,

- replaced by a revised edition, or
- amended.

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INTRODUCTION

The purpose of this Technical Specification (TS) is to define a common basis for the management of physical and digital assets associated with wind farms throughout the operating life. The objective is to ensure the integrity of the structure whilst operating, both within the design life and beyond. The focus of the guidance in this TS is safety, defined as ensuring the structural integrity of the components in the primary load path of a given turbine or site and the continued function of critical systems. It is anticipated the reader will make an assessment of risks and uncertainties, aligned with safety, technical and commercial requirements of the particular project, in order to determine the level of detail justified for any assessments undertaken.

This TS has been published to enable wind farm operators to manage the production of electricity from wind turbines for the longest possible safe period of time, averting the unnecessary social and environmental costs of premature decommissioning. Defined here are the procedures for amassing the minimum body of evidence to justify continued operation.

It is highlighted here that the cumulative uncertainty, as defined in ISO/ IEC guide 98-3 and estimated using methods defined in this TS, including uncertainties in calculations, shall be used to estimate the variability of the results. This variability shall be stated alongside any estimates of remaining life of components.

Regarding risks to personnel or third parties, no attempt is made to incorporate the many individual interpretations by regulatory authorities in different regions or jurisdictions.

The earlier in the wind farm operational life the guidance in this TS is implemented the better, but suitable procedures may be developed and followed, by any stakeholder, at any point in the life of a wind farm. The guidance should be applied to each mode of failure for each component in the primary load path and associated critical systems. Estimates of life may be made, relating to the most significant mode of failure and taking full account of specific conditions at the site and operational practices. Phases of operation, at which this guidance may be applied, include amongst others the following:

- Reviews of site-specific assessed life prior to construction
- Site specific expected life at end-of-warranty
- Points of re-financing and sale
- Proposed extended operation beyond the site specific assessed life.

The guidance may be used by designers, manufacturers, developers, operators or third parties and may be used as part due diligence. Application by stakeholders of practices and techniques specified in this TS may be used to minimise costs of operation and maximise safe, useful, productive life. In particular, recommendations are given and approaches described for the assessment of the following example situations:

- Historical duty, usage and working life consumed,
- current component health and
- expected future remaining life.

These may be used to assess the condition and productivity of individual turbines, safety systems and the primary structure at specific turbine locations within a wind farm or comprehensively for all locations of a site. The principles defined, practical guidance and theoretical techniques described may be used to update the expected useful life of the assets. Additionally, assessments of expected technical availability, reliability and safe operation beyond the end of the design life may also be made. Availability shall be defined according to IEC TS 61400-26-1 [N.10] and IEC TS 61400-26-2 [N.11].

IEC-61400-1, -2 and -3 [N.1], [N.2], [N.3] contain minimal requirements for design ensuring structural integrity of wind turbines, under standardized classes of meteorological conditions and operational practices. Also included are many other contextual conditions affecting loading and expected life. IECRE OD-502 [N.24] describes certification of a wind farm project. If the wind farm is certified, loads analysis, will be used to estimate site specific life prior to construction. IEC-TS-61400-28 is the only document amongst the IEC-61400 series, which describes the following:

- Updating the life (estimated prior to construction) for a specific site
- Operated under specific site conditions and management procedures
- Showing symptoms of degradation, having experienced specific modifications
- Faults or failures, taking into account evidence of turbine reliability
- Changes of operational status
- Including starts, stops, errors, warnings, curtailment, sector management and grid outages.

It is recommended to re-assess the life on this basis at regular periods during the life of the wind farm. In particular, it should be assessed whether or not it would be safe to continue operation of the wind farm, beyond the expected life or beyond that claimed in the type certificate, if available for the wind turbine. Turbines may be safe and suitable to produce additional electricity, either during or beyond the site-specific life. It is important to note that these are estimates of remaining life, whether based on observations, measurements, statistical methods or simulations. The actual life, with respect to the most significant mode of failure, may be longer or shorter.

It may be appropriate to adjust the values of factors of safety or uncertainties, which were applied prior to construction at the design stage, associated with key parameters required to estimate integrity and life. Evidence to support any such adjusted values must be provided, whether through applying best practices of wind farm operation, collecting information about the conditions at each turbine, the production, the maintenance tasks undertaken, the condition of critical components, the modes of failure and their consequences.

This technical specification may be used to define the technical inputs to any economic assessments, developed by stakeholders to value assets throughout their life, but does not describe any particular economic models.

The focus of this edition is on components in the primary load path and the safety system. For loading and structural integrity, accumulation of fatigue damage is described in this TS. Regarding ultimate limit states however, comprehensive guidance is not given about methods to reassess and update the statistics of extreme conditions, faults and failures, which contribute to the ultimate limit state. Detailed analyses of the reliability of components outside the primary load path are not described here, even though these aspects may contribute to the objectives of this technical specification. It is left to the reader to extend the methods described in this TS if relevant to topics relating to component reliability, with reference to IEC 61400-26-4 [N.12].

1 Scope

This technical specification sets out minimum requirements for actions, investigations and assessments to ensure the continued structural integrity of wind farm assets, particularly wind turbines, aimed at verifying that they remain safe for personnel to operate. It is strongly recommended to maintain those assets and collect suitable evidence to demonstrate to third parties that risks are minimised, particularly where risks relate to collateral damage or injury, such as may be suffered by personnel or structures neighbouring the wind farm.

Covered in this document are assessments of current condition and remaining useful life, resulting in the technical basis for justifying extended operation beyond the design life (defined in Clause 3.1.3) and also beyond the site specific assessed lifetime, whichever is shorter, for structural or major components and systems contributing to primary layer of the safety system. Guidance is also given on how best to manage a wind farm throughout the operational life.

2 References

2.1 Normative references

[N.1] IEC 61400-1 Wind energy generation systems Part 1: Design requirements

[N.2] IEC 61400-2 Wind energy generation systems Part 2: small wind turbines

[N.3] IEC 61400-3-1 Wind energy generation systems – Part 3-1: Design requirements for fixed offshore wind turbines

[N.4] IEC 61400-6 Wind energy generation systems – Part 6: Tower and foundation design requirements

[N.5] IEC 61400-12-1 Wind energy generation systems – Part 12-1: Power performance measurements of electricity producing wind turbines

[N.6] IEC 61400-12-2 Wind energy generation systems – Part 12-2: Power performance measurements of electricity producing wind turbines

[N.7] IEC 61400-13 Wind Turbines – Part 13: Measurement of mechanical loads

[N.8] IEC 61400-25-1 Wind energy generation systems - Part 25-1: Communications for monitoring and control of wind power plants - Overall description of principles and models

[N.9] IEC 61400-25-2 Wind turbines - Part 25-2: Power performance of electricity-producing wind turbines based on nacelle anemometry

[N.10] IEC TS 61400-26-1 Time based availability for wind turbine generating systems

[N.11] IEC TS 61400-26-2 Production based availability for wind turbines

[N.12] IEC TS 61400-26-4 Wind energy generation systems Part 26-4: Reliability (due 2021)

[N.13] API 581:2000 Risk-based inspection base resource document

[N.14] IEC 60300-3-11 Dependability management - Application guide – Reliability Centred Maintenance

[N.15] IEC 81346-1 Industrial systems, installations and equipment and industrial product — Structuring principles and reference designations

[N.16] IEC 60812 Failure modes and effects analysis (FMEA and FMECA)

[N.17] IEC 61025 Fault tree analysis (FTA)

[N.18] IEC 61703 Mathematical expressions for reliability, availability, maintainability and maintenance support terms

[N.19] EN 50308-2004 Wind turbines – Protective measures – Requirements for design – operation and maintenance

[N.20] ISO 13849-1 Safety of machinery -- Safety-related parts of control systems -- Part 1: General principles for design

[N.21] ISO 13372 Condition monitoring and diagnostics of machines - Vocabulary

[N.22] ISO 16079-1 Condition monitoring and diagnostics of wind turbines Part 1: General guidelines

[N.23] IECRE OD 501 Type Certification Scheme

[N.24] IECRE OD 502 Project Certification Scheme

[N.25] ISO 19902 Petroleum and natural gas industries – Fixed steel offshore structures

[N.26] ISO 19903 Petroleum and natural gas industries — Fixed concrete offshore structures

[N.27] ISO Guide 98/3 Uncertainty of measurement, Part 3 - Guide to the expression of uncertainty in measurement (GUM:1995)

[N.28] ISO 2394 General principles on reliability for structures. International Organization for Standardization, 2015.

[N.29] ISO 13822 Bases of design for structures – Assessment of existing structures

[N.30] ISO 16079-1 Condition monitoring and diagnostics of wind turbines Part 1: General guidelines 2017

[N.31] IEC 61511-1 A1 2017 Functional Safety instrumented systems application programming requirements

[N.32] IEC 61511-2 Functional Safety instrumented systems Guidelines application

[N.33] WMO Guidelines on Climate Data and Homogenization. WMO-TD No 1186.

[N.34] ISO 13381-1 Condition monitoring and diagnostics of machines - Prognostics - Part 1: General guidelines

[N.35] ISO 17065 Conformity assessment - Requirements for bodies certifying products, processes and services

[N.36] ISO 17025 General requirements for the competence of testing and calibration laboratories

[N.37] EN 1990 Basis of structural design

[N.38] IEC 61400-3-2. Wind energy generation systems. Part 3-2. Design requirements for floating offshore wind turbines

2.2 Informative references

[I.1] UL ANSI 4143. Wind Turbine Generator – Life-time Extension (LTE)

[I.2] IEC 60204 32 2008. Safety of machinery - Electrical equipment of machines - Part 32 Requirements for hoisting machines

[I.3] ISO 55000, 55001 and 55002. Asset Management

[I.4] ISO 4406:1999. Hydraulic fluid power - Fluids - Method for coding the level of contamination by solid particles

[I.5] ISO 4021:1992. Hydraulic fluid power - Fluids - Particulate contamination analysis -- Extraction of fluid samples from lines of an operating system

[I.6] ISO 281:2007. Rolling bearings - Dynamic load ratings and rating life

[I.7] IEC 61400-25-6. Communications for monitoring and control of wind power plants - Logical node classes and data classes for condition monitoring

[I.8] ISO 13373 series

[I.9] IEC 62079:2001. Preparation of instructions - Structuring, content and presentation

[I.10] IEC 60050-192:2015. International electrotechnical vocabulary – Part 192: Dependability

[I.11] Sørensen, JD, Toft, HS. Safety Factors – IEC 61400-1 ed. 4 – background document. DTU Wind Energy-E-Report-0066(EN), November 2014

[I.12] Sørensen JD, Frandsen S and Tarp-Johansen NJ. Effective turbulence models and fatigue reliability in wind farms. Probabilistic Eng Mech 2008; 23: 531–538.

[I.13] JCSS model code for probabilistic assessment of structures (https://www.jcss-lc.org/jcss-probabilistic-model-code/)

[I.14] IEC 61882:2016. Hazard and operability studies (HAZOP studies) – Application guide

[I.15] ISO 31000:2018. Risk management – Guidelines

[I.16] IEC 31010:2019. Risk management – Risk assessment techniques

[I.17] ISO 9001:2015. Quality management systems

[I.18] ISO 45001:2018. Occupational health and safety management systems

[I.19] ISO 8000. Acquisition of data and information.

[I.20] RDS-PP. Reference designation system for power plants.

[I.21] BS EN ISO/IEC 17025:2017. General requirements for the competence of testing and calibration laboratories.

[I.22] ISO/TS 16281 Rolling bearings - Methods for calculating the modified reference rating life for universally loaded bearings

[I.23] IEC 61400-4 Wind energy generation systems – Part 4: Design requirements for wind turbine gearboxes

3 Definitions and abbreviations

3.1 Definitions

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

3.1.1 Boroscope inspection

Visual inspection (generally of inaccessible internal parts of components) facilitated by the use of a fibre-optic or camera mounted on the end of a flexible conduit.

3.1.2 Condition monitoring (CM)

Acquisition and processing of information and data that indicate the state of a machine over time.

Note to entry: The machine state deteriorates if Faults or Failures occur.

SOURCE: ISO 13372 [N.21].

3.1.3 Design life (see Table 1)

The period of wind farm/wind turbine/structural component operation at the end of which the minimum required structural integrity according to the adopted design standard (the version of IEC 61400-1 [N.1], IEC 61400-2 [N.2] or IEC 61400-3 [N.3] series which was applicable at to time of the turbine design) is still ensured. For example, it is a minimum of 20 years for turbine classes I to III, with respect to operation in accordance with IEC-61400-1:2019 [N.1] and the IEC-61400-3-1:2019 [N.3]. For turbine class S, a different design life shall be defined. Design life is also called type certified design life (TCDL) where it is defined by the OEM as part of a process of type certification and recorded on the type certificate and related documentation. Several definitions of remaining life are used in this TS and distinguished in Table 1.

3.1.4 Detection

The action or process of identifying the presence of something concealed.

3.1.5 Failure

Termination of the ability of an item to perform a required function.

SOURCE: ISO 13372 [N.21]

3.1.6 Fault

Condition of a machine that occurs when one of its components or assemblies degrades or exhibits abnormal behaviour, which may lead to the failure of the machine.

SOURCE: ISO 13372 [N.21]

Note to entry: identification of an existing Fault is the result of CM process (from data issued from inspections, SCADA and/or CMDs to information, from information to Symptoms).

3.1.7 Information

Interpretation of measurements, for example, to provide status or evaluation of health (e.g., by comparison with tables, thresholds or standard values).

3.1.8 Inspection

Investigation of current condition or health, through physical attendance at the wind turbine, by qualified personnel.

3.1.9 Lifetime extension/Life extension

Operation beyond the expected duration of safe operational life, specified for any major or structural component of the wind turbine in the type certificate or according to estimates of site-specific assessed life and/or site-specific expected life, if shorter.

3.1.10 Measurements

Numerical information collected by sensors or by physical attendance at the wind turbine by qualified personnel. No interpretation of the resulting data is implied by the term.

3.1.11 Measurement campaign

Limited duration exercise to collect time series of measurements, either by sensors and data-loggers, existing SCADA and condition monitoring equipment or repeated, direct, manual measurements by qualified personnel.

3.1.12 Metallurgical examination

Assessment of material properties via testing and/or microscopy.

3.1.13 Monitoring

Observe and check the progress or quality of something over a period of time; keep under systematic review.

3.1.14 Non-destructive testing

Collective term to describe means for inspecting components for defects (either surface or subsurface defects) without causing damage to them.

3.1.15 Remaining useful life (RUL, see Table 1)

Remaining time before system health falls below a defined failure threshold

Note to entry: In the current technical specification, RUL is defined as the remaining time for which structural integrity and industrial safety is ensured regarding hazards to the environment and personnel. The estimate of RUL should include all relevant design safety factors, margins of safety due to uncertainties with site data, model parameters, methods and assumptions, with regards to components in the primary load path. If structural components are exchanged, RUL of the system may be recalculated after exchange.

SOURCE: ISO 13381-1:2015: Condition monitoring and diagnostics of machines - Prognostics - Part 1: General guidelines [N.34]

3.1.16 Site specific evaluation

The term SSE is not used in this technical specification because what is being assessed is the suitability of the turbine for continued operation, rather than the original design of the turbine.

3.1.17 Site specific turbine suitability assessment

Assessment of suitability of wind turbine for particular wind farm, based on turbine design loading envelope, characteristics of the site and wind conditions, together with operational strategy (including, for example, strategies regarding condition monitoring, inspections, maintenance, service and electricity production). SSDE is often undertaken as part of wind farm project certification, in accordance with IECRE OD 502 [N.24], Clause 6.3 (site suitability evaluation). The procedure followed by the reader of IEC-TS-61400-28 should align with the requirements of IEC-61400-1 [N.1], Clause 11 and Annex B for site-specific turbine suitability assessments.

3.1.18 Site specific assessed life (see Table 1)

The theoretical period of a specific project/wind farm/wind turbine/structural component operation computed or calculated after site assessment under specific local conditions, at the end of which the minimum required structural integrity and industrial safety is still ensured. This information shall be calculated with the site assessment information (without guarantee but including uncertainty estimates). It is likely that the wind class in the specified external conditions will differ from site-specific operating conditions. The SSAL estimate is based on the components supplied to the project and thus may be designated as “prior to construction”. Prior experience regarding reliability and modes of failure should be taken into account, if available.

3.1.19 Site specific expected life (see Table 1)

At any moment during the operation, the SSEL is the estimated safe operating life of a specific project/wind farm/wind turbine/structural component operating under specific local conditions, at the end of which the minimum required structural integrity and industrial safety is still ensured. In general, the SSEL will depend on repairs, refurbishment and retrofits, including software updates.

Examples of modifications include those observed with meteorological conditions, inspections or campaigns of measurements, those made to condition monitoring, specific defects or failures, together with corresponding RCAs/repairs/exchanges/upgrades, operational strategy (including, for example, strategies regarding health monitoring, inspections, maintenance, service and electricity production) and turbine components. SSEL is the total time passed since commissioning and the anticipated RUL. It may be greater or less than the design life or site-specific assessed life.

3.1.20 Structural or major components

Any component (including safety devices) of the turbine that is load carrying and/or whose failure could be critical, resulting in a catastrophic consequence such as severe injury or death of personnel, large parts thrown or falling, or collapse of the turbine. Identification of major components will usually result from FMECA of the particular turbine design. The list of major components included here for the wind turbine is defined as, but not limited to, the following.

- Primary load path
  - blades
  - pitch bearings and pitch drive
  - hub
  - main shaft
  - main shaft bearings
  - main shaft bearing housing(s) and 3 or 4-point connections, torque arm (3 point connection)
  - gearbox (if structure comprises part of load path)
  - gearbox mounting structures
    - gearbox structures that react rotor torque
    - gearbox structures that react brake or high speed rotor lock torque
    - shrink disc coupling connections
  - nacelle baseplate
  - yaw bearing and drive
  - tower
  - bolted connections (of components listed above)
  - foundation
  - secondary systems
  - generator (if structure comprises part of load path)
- Control and protection systems
  - major electrical protection systems
  - transformer
  - MV switchgear
  - converter and other major electrical protections
  - transformer
- Safety systems (refer to IEC 61511 series [N.31], [N.32])
  - overspeed detection
  - primary braking

- pitch actuation
- systems to ensure aerodynamic braking in the event of power failure
- secondary braking
- fall arrest on the elevator
- fall arrest on the ladder

3.1.21 **Structural health monitoring**

Real time tracking of parameters correlated with the state of health of part of the primary structure.

SOURCE: ISO 61400-6 [N.4]

3.1.22 Symptom

Perception, made by means of human observations and measurements, which may indicate the presence of one or more faults.

SOURCE: ISO 13372 [N.21]

3.1.23 Tolerance

Permitted deviation between the declared value of a quantity and the measured value.

Source: Electropedia

3.1.24 Through-life management

All activities relating to operation and management of the wind farm by the owner or designated agent. It is strongly recommended that the wind farm owner or operator investigates, records, understands and acts upon the safety and reliability of the wind turbines at all times during the operational phases. The activities required include remote operation and monitoring, condition monitoring, collection, retention and interpretation of data, fault diagnosis, repairs, replacement of defective parts, RCAs, upgrades, maintenance advice, inspection, feedback from other operators, reliability analysis, assessments of current health and estimates of remaining useful life.

3.1.25 Type certificate (design)

Wind turbine type certificates document evaluation of the loading and design life for particular conditions, which may correspond to wind turbine type classes or those which relate to specific wind farms. Older wind turbines, currently in operation may not be accompanied by such a type certificate. In such cases, best available information shall be sought as to the suitability of the original turbine design to the specific wind farm site conditions. Wherever the term Type Certificate is used in this document, the best available information about the original or modified design shall be used.

3.1.26 Wind farm

All components required to generate and supply electricity to the local grid, including turbines, foundations, electrical and civil infrastructure.

3.2 Abbreviations

AAN	accuracy assessment numbers
ALARP	as low as reasonably practicable
AMS	asset management system
CM	condition monitoring
CMD	condition monitoring devices

CMS	condition monitoring systems
CoG	centre of gravity
COV	coefficient of variance, ratio of the standard deviation to the mean of a random variable
FEA	Finite element analysis
FMEA	failure modes and effects analysis
FMECA	failure modes, effects and criticality analysis
HSE	health, safety and environment
ISP	independent service provider
LPS	lightning protection system
LTE	lifetime extension /life extension
NDE	non-destructive evaluation
NDT	non-destructive testing
OEM	original equipment manufacturer
PAUT	phased array ultrasonic testing
PPM	parts per million
RBI	risk-based inspection
RCA	root cause analysis
RCM	reliability centred maintenance
RPM	revolutions per minute (of a shaft, wheel or applied to any cyclical time series)
RUL	remaining useful life
SAP	systems applications and products
SCADA	supervisory control and data acquisition
SD	standard deviation
SHM	structural health monitoring
SHMD	structural health monitoring device
SSAL	site specific assessed life
SSE	site specific evaluation (not used in this technical specification)
SSTSA	site specific turbine suitability assessment
SSEL	site specific expected life
TCDL	type certification design life – being the design life assumed for wind turbine type certification (usually 20 years)
TLM	through life management

TS	technical specification (acronym denotes this document, IEC-TS-61400-28)
VMS	vibration monitoring system
WF	wind farm
WTG	wind turbine generator
WTI	wind turbine improvement document
WTR	wind turbine retrofit document

Table 1 – Comparison between definitions of remaining life used in this TS

Questions below are intended to be used as prompts, assisting in the definitions of the terms defined below (TCDL, SSAL and SSEL). The answers indicate whether or not the requirements of these design life estimates have been met.	
(a)	Has the turbine or relevant component been categorised by standard type class conditions?
(b)	Is the turbine designated class ‘S’ with minimum deviations from standard type classes?
(c)	Has the site been characterized prior to construction using accurate meteorological and metocean data?
(d)	Has the site characterization been verified during the operational phase? (including operation of the wind farm, grid outages, statistics of observed turbine starts/stops/idling)
(e)	Has the risk profile of the component been estimated (failure modes, effects & criticality analysis)?
(f)	Has the historical performance of similar components been captured (failure rate, locations of damage experienced in the past, repair history, published databases, operator’s own experience, FEA, NDT)?
(g)	Has the current health of the component been assessed (physical, onsite inspections)?
(h)	Have measured data been used to estimate rates of failure (SCADA, collected from structural health monitoring/condition monitoring devices or campaigns of measurements/using machine learning or artificial intelligence)?

Definitions and consistent usage throughout IEC-TS-61400-28

remaining life	(a) or (b) WTG type certificate	(c) site met. conditions, prior to construction	wind farm operational	(d) site met. operational conditions	(e) FMECA	(f) failure history	(g) component current health	(h) measured data
TCDL	×							
SSAL	×	×						
SSEL	×	×		×	×	×	×	×

Note that the difference between the site specific assessed life and the site specific expected life is the greater level of confidence in the latter due to the combination of more accurate data and more sophisticated models. In particular component failure data and the results of inspections shall be evaluated by means of a site specific turbine suitability assessment (SSTSA) to improve SSEL estimates.

4 User guidance: Concept of through-life management and lifetime extension

4.1 Overview

This Clause is intended to give guidance to the reader about optimal implementation of this technical specification and to introduce best management practices to be applied throughout the operational life of the wind turbine asset and during a potential phase of extended operation.

The objective of this technical specification is to enable wind turbine owners or operators to ensure the integrity of the asset during the design life and beyond ("lifetime extension"). The primary focus is on the main load carrying components and critical systems. Some recommendations are also given relating to protection systems, electrical installations and equipment associated with health or safety of personnel. Stakeholders may apply the specified practices and techniques to achieve the following objectives:

- Fine tune the asset management approach for maximizing asset lifetime
- Fine tune the asset management approach for increasing yield within a certain time frame
- Provide the technical evidence basis for informing the business case with regards to particular strategies such as the following
  - lifetime extension, potentially facilitated by:
    - investment in additional condition monitoring hardware or software
    - increased frequency inspections
    - replacement of major components
    - changes of operating strategy
    - additional maintenance strategies
  - yield optimisation throughout the operational life
  - optimisation of wind farm management with regards to OPEX, inspections and availability
  - repowering
  - decommissioning

This Technical Specification may be applied at any stage during WTG life cycle: for new turbines (from planning to take over), for turbines already in operation and for aging turbines later in life where lifetime extension is under consideration. In addition, the technical specification may be applied based on:

- Different strategies regarding management of turbine operation
- Different levels of knowledge about the turbine
- Different levels of confidence in the methods selected
- Information used as inputs to the analysis.

Practical experience shows there are many differences between designed and installed systems. The former includes the behaviour assumed prior to construction and used for assessments of safety or operational life. The latter comprises structures and equipment in the operational wind farm. This TS addresses these differences and strongly recommends updated estimates, based on accurate operational experience, data, assumptions and models of behaviour, as indicated in Figure 1.

In accordance with the requirements of IEC 61400-1 [N.1], assessment of the integrity of the primary structure shall comply with the principles described in ISO 2394 [N.28] (in particular Annex B). As directed in ISO 13822 [N.29], lower levels of structural reliability may be justified for existing structures because of the elevated costs of increasing the resistance. The strength of the structure may be shown to be inadequate to achieve the structural reliability required by the edition of IEC 61400-1 applicable at the time of design of the wind turbine in cases in which there have been:

- changes of loading from that assumed during design,
- changes in the governing design standards,

- damage,
- corrosion,
- operation beyond the lifetime assumed during design,
- or other consequences of operation.

Where a lower target reliability is used, the consequences for human safety shall be assessed. The autonomous unattended operation of the wind turbine shall be reviewed in the light of any changes of use of spaces in the vicinity and, as a minimum, evidence shall be provided that technicians can continue to work safely at the facility, at least for decommissioning tasks.

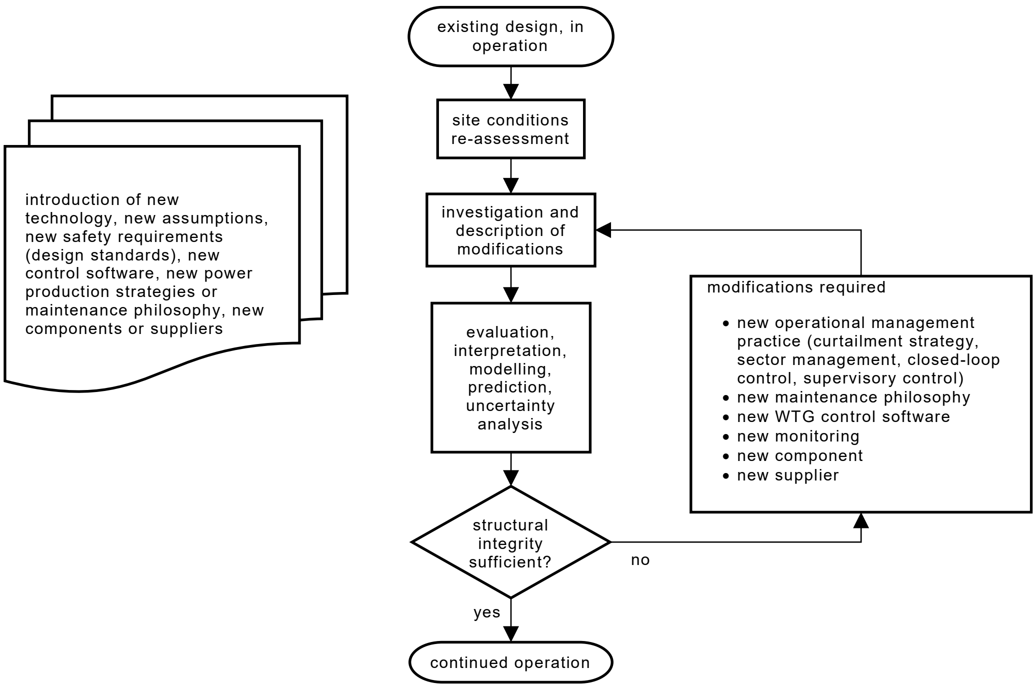

Figure 1: Updated assessments and estimates of component safety and remaining life

The owner or operator may use the level of confidence to classify a given wind turbine, regarding its condition and RUL. This level of confidence can be increased using some or all of the techniques presented in this technical specification (see Figure 2). These processes alone do not necessarily lead to an extension of the lifetime of the asset, but may increase the certainty (level of confidence) with which an owner or operator can predict the remaining useful life. It is important to underline that, throughout this Clause, the term "level of confidence" should not be interpreted as the remaining time the asset can be safely operated, but rather it reflects the accuracy of the RUL estimate. However, the level of confidence is an important factor and fundamental to the philosophy of this technical specification, since it has a direct bearing on the estimates made and the use to which they may be put. As an example, a low level of confidence could result in a premature decommissioning, simply because not enough information is available to allow for safe continued operation. Usually, the precautionary principle will be applied such that the RUL will be accepted to be the lowest estimate, taking uncertainties into account. Decisions may be based on the P95 value of RUL, again dependent on uncertainties.

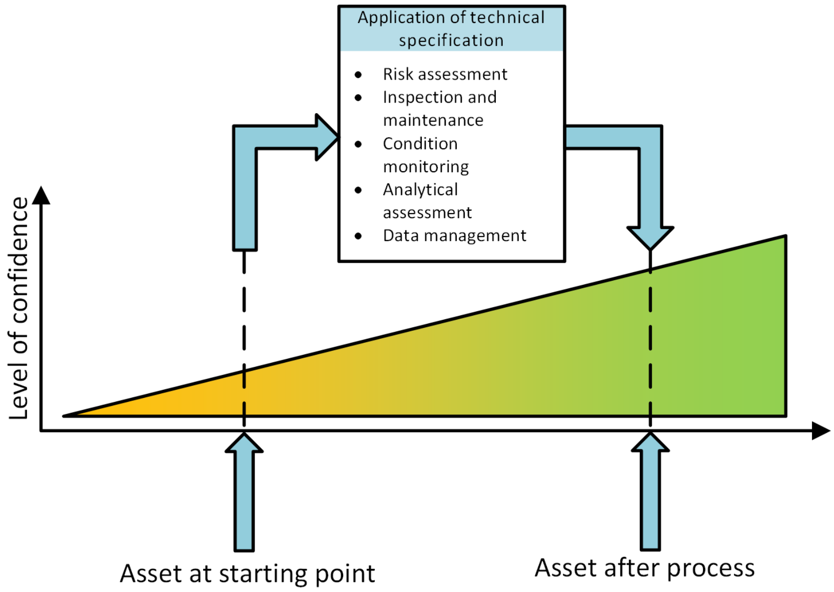

Figure 2: An illustration of how the level of confidence can be improved by applying this technical specification (for example, relating to the estimated RUL)

Figure 3 shows three typical phases of operation of a wind turbine asset and illustrates how the methods described in this technical specification may be applied repeatedly throughout the life.

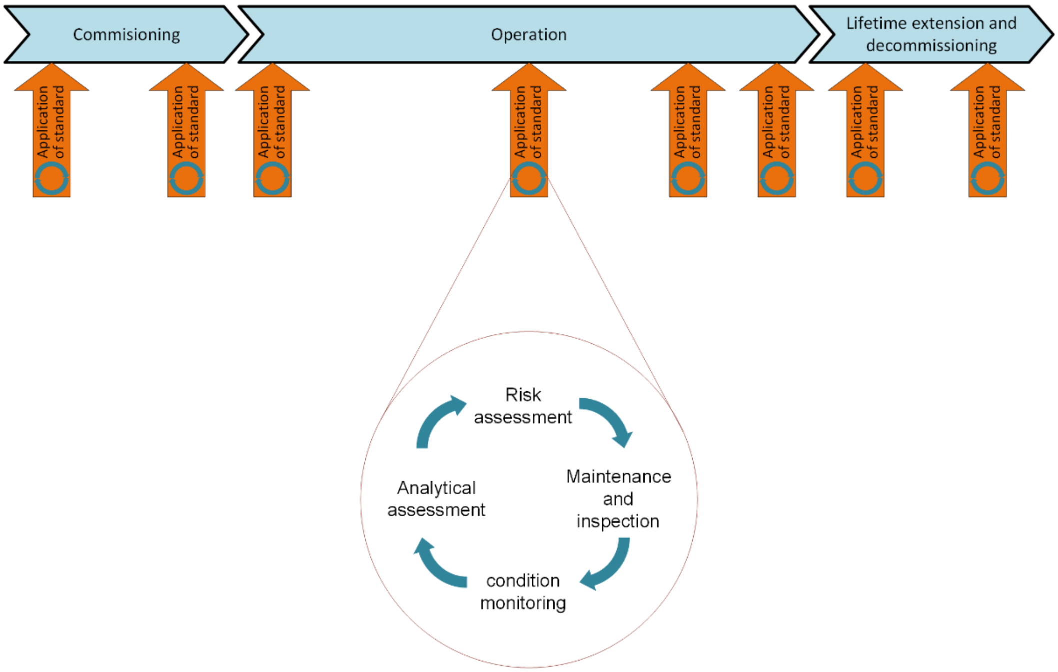

Figure 3: This technical specification can be applied at any time during asset lifetime and there are benefits from starting early and repeating the analyses described

The consequences for the predicted RUL of implementing the methods described in this technical specification are illustrated in Figure 4. Here, the slopes of the red, blue and green curves represent the theoretical or estimated "deterioration rate" for the wind turbine asset or a component in the asset. The solid red line illustrates an asset which is poorly maintained and operating in very adverse ambient conditions (a worst-case scenario), whereas the solid green line illustrates an asset which is very well maintained and operating in very favourable ambient conditions (a best-case scenario).

The blue line illustrates an example of an actual asset. The slope of the blue line (the perceived deterioration rate of the blue asset) is not necessarily a consequence of an actual physical deterioration, but is the rate at which the asset is thought to age, considering the knowledge, or lack of knowledge of its current condition, operating conditions, repair state etc at the given time. At the time of application of this technical specification (the yellow dot), methods are applied which lead to a more accurate estimate of the deterioration rate (dotted green curve or dotted red curve).

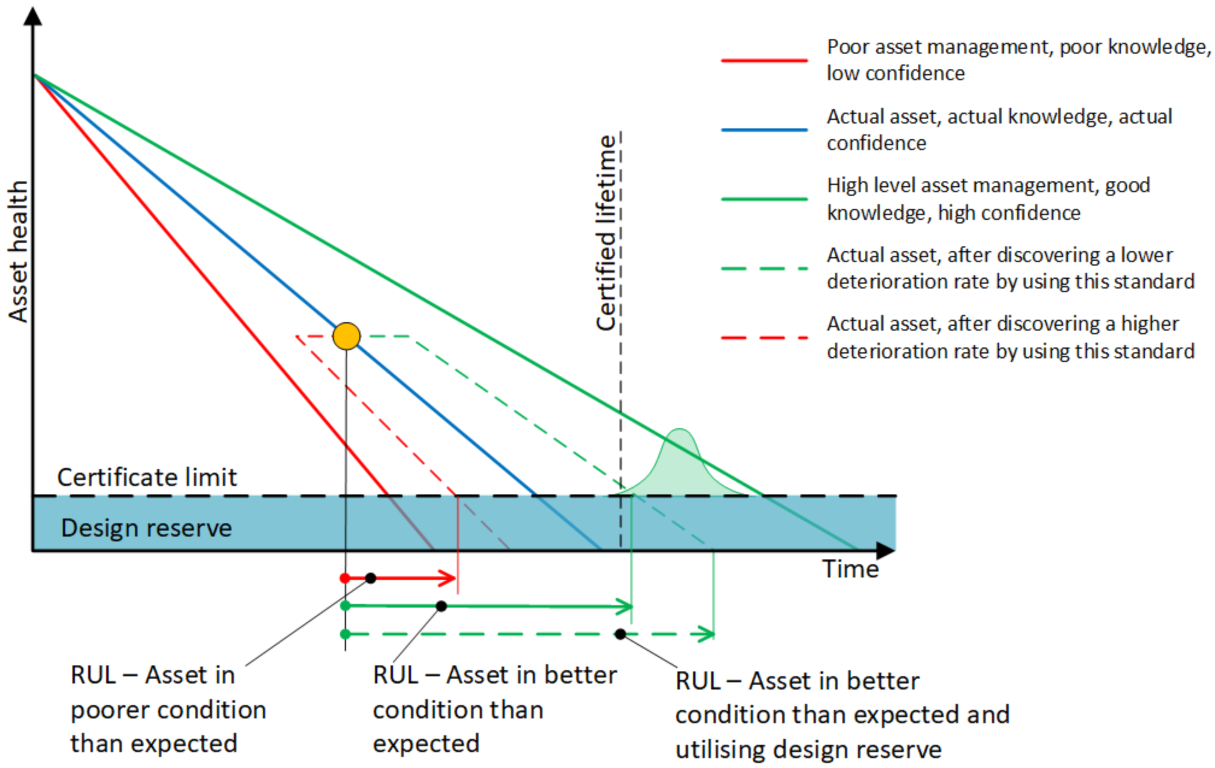

Figure 4: Effect on asset life due to improved strategies and increased levels of confidence.

If evidence (for example by inspection, condition monitoring or structural health monitoring) indicates components in the critic,al load path are in better condition than expected, at the time guidance in this technical specification is applied, a new lower rate of deterioration (dotted green curve) may be justified, leading to an extended RUL. This may be because of the introduction of a new approach to maintenance or condition monitoring (providing improvement relative to the previous approach), or the observed ambient site conditions are less severe than assumed (for example, turbulence intensity). It may actually be that this lower deterioration rate would have been appropriate from the start of the asset life, hence the short horizontal displacement of the green line.

If it is revealed that the structural or major components are in a worse condition than expected or if the ambient conditions are more severe than anticipated, then the appropriate slope would be steeper (dotted red curve) leading to a shorter RUL prediction. Again, the conditions may have been present since start of life, leading to a horizontal offset.

The short horizontal displacement of the curves is important. If, for example, it is found that the ambient site conditions are more severe (for example, due to higher turbulence from a neighbouring wind farm which was erected after the asset was installed), it is important that this new information is included in the total consumed life estimate of the asset, not just from the time of the implementation of this Technical Specification, but throughout the operational phase the information is relevant.

In the example in Figure 4, it is seen that the dotted green curve leads to a RUL estimate which exceeds the expected lifetime of the asset (estimated during the process of type certification), and hence extended operation beyond this point in time has been justified.

Also important are the uncertainties associated with all data, information and estimates made, indicated by the Gaussian curve used as an example in Figure 4. This is only shown for the favourable green dotted line, but uncertainty assessments are to be applied to all aspects of any assessment of condition or RUL.

Figure 4 also shows how, at the end of the lifetime which is predicted as part of the process, the life of the asset may be extended even further by utilizing knowledge of built-in design reserve in the asset structural or major components. Such design reserves are normally included as safety factors that account for:

- variability of material properties,
- environmental loading,
- operational practices,
- variability of aspects of manufacture,
- transportation,
- assembly,
- installation,
- condition monitoring,
- access for inspection.

These have been taken into consideration during the process of type certification. At a late stage in the life of an asset, this variability may no longer be unknown, and the actual conditions would be known with much greater certainty offering a potential to re-evaluate and adjust safety factors. Detailed knowledge of the turbines design would be required to change the safety factors and evidence of the reduced variability shall be provided before doing so. Estimates of the RUL should be based on the real current condition of the asset incorporating aspects of the operational environment and procedural strategy, anticipated in the future. Examples of important contextual information, historical and future, include extreme events, damage identified through physical inspection or electronic sensors, loading and risk profiles. Finally, all estimates are subject to variability, due to differences in assumptions, model veracity, values of key parameters and characterisation of the operating environment. This variability is indicated in Figure 4 by the symbol of a Gaussian probability distribution superimposed on the estimated RUL. Examples of wind farm management affecting the deterioration rate include those in the following list:

- Monitoring of lubricant cleanliness and replacement if necessary
- Mitigation and repair strategy concerning:
  - damage to welds
  - edge contact between rolling element and bearing raceway
  - pitting, spalling, corrosion
  - non-linear buckling of composite elements of the blade structure
- Change of strategy regarding curtailment, power set-point, high-speed cut-out, aerodynamic performance of blades
- Changes to software settings

4.2 Data management

Thorough approaches to data management are emphasised in this Technical Specification. At all stages of the operational life, it is recommended to maintain comprehensive records and interpret data appropriately. This includes documenting the assessment methods applied, any assumptions made and the outcomes. Such information can, at a later stage, serve to increase the level of confidence. Detailed recommendations and methods for data management are given throughout the technical specification and specifically in Clause 5.

4.3 Reading guideline

This Clause aims to guide through some specific parts of the Technical Specification. This is done via the illustration in Figure 5 of a typical asset management process. By implementing the processes described in this Technical Specification, assets may be managed throughout the life more effectively and the potential for lifetime extension may be estimated more accurately. Combinations of different methods will be selected depending on the context, available data, application of different asset values held by different stakeholders, budget available for undertaking studies and gathering data.

The individual steps in Figure 5 are applied at different levels and with different outcomes at different stages in the asset life. Some steps may be omitted, but through life management shall include the following:

- Decisions should be based on a thorough risk management process
- Inspection/maintenance scheme should be reviewed and optimized (instigated if not initially present)
- Condition monitoring scheme should be reviewed and optimized (instigated if initially inadequate for assessment of asset health with respect to the most significant risks or modes of failure, at sufficiently frequent time intervals)

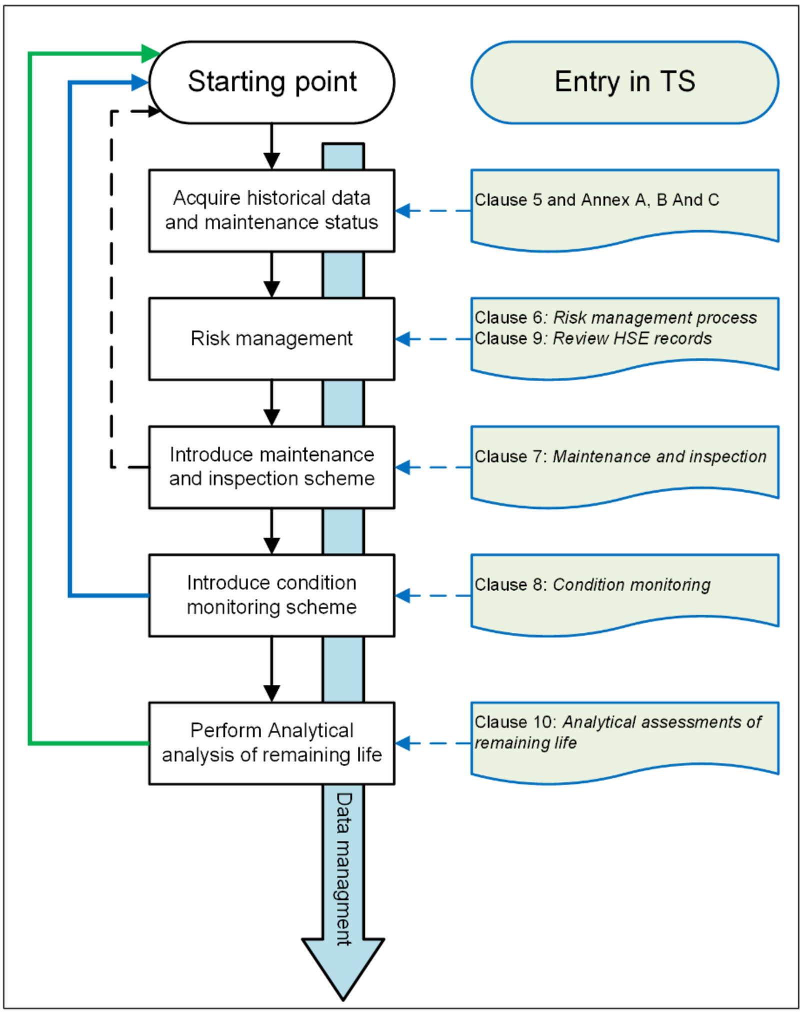

Figure 5: The process of through life management and lifetime extension. Data management is the backbone of the process

Step 1: Acquire historical data and maintenance status

This step precedes all others and is a vital part of the planning phase. Included are data used to characterise the site, especially wind speeds and turbulence. Even if an asset has been run and maintained by the same operator for its entire lifetime, it will always be vital that information is gathered about the maintenance history, any exchanges of major components and loading history.

This step also includes gathering information about ambient conditions and any changes over time. This could, for example, be changes in turbulence due to newly erected buildings, growth of forests or neighbouring wind turbines. For a newly acquired asset, this step may be even more important and could comprise an element of technical due diligence informing the commercial aspects of a change of ownership, new investment or change of responsibility for management of the asset.

Annex B (*Data requirements for primary load path*) describes which information is important for assessing the loading history of components. Clause 5 (*Data management, requirements and uncertainty*) gives general recommendations regarding collection and storage of data generated during the asset lifetime. Recommendations are also made regarding sources and categories of information.

Step 2: Risk management process

Prior to commencing any new asset management activities or gathering evidence to inform decisions about extended operation, the risks should be assessed, categorised and ranked. This enables the focus for these activities to be defined based on an improved knowledge of the modes of failure and their relative significance.

Clause 6 (*Risk management process*) provides guidance on the assessment and ranking of risks. A risk assessment will help to prioritise efforts in the further steps.

This risk assessment could, for example, indicate higher risk associated with components or structures that have been heavily loaded or are nearing the end of their lifetime. For the latter, simply continuing with established or supplier-defined service instructions may not suffice. Adoption of new measures may need to be considered.

It should be assessed if failure consequences assumed prior to construction are still valid. For example, because of proximity to new structures or increased public access.

Step 3: Operation, maintenance and inspection

Following the risk assessment process, a maintenance and inspection scheme can be drawn up, as described in Clause 7 (*Wind farm operation, maintenance and inspections*).

If no previous maintenance records exist, it is advisable to assume that service requirements and adequate equipment maintenance have not been implemented. Maintenance records will need to be brought up to date.

This could comprise a combination of inspection and maintenance tasks, including, for example, bolt inspection and re-torquing, non-destructive evaluation of welds, analysis and replacement of oil or grease, replacement of filters, inspection of brake pads.

If the maintenance schedule has been followed, the risk assessment described previously may still provide justification for extra measures beyond the service instructions. These may comprise new data processing algorithms, new condition monitoring devices or increased-frequency inspections.

After inspections, it is valuable to repeat Step 2, obtaining a new risk ranking and improved estimate of RUL. This improved knowledge would be helpful in Step 4.

Step 4: Condition monitoring

This task comprises the steps described in Clause 8 (*Condition monitoring*).

Generally, condition monitoring provides a continuously updated picture of the asset health which can be used to update numerical models, to optimize operation, to predict and detect failures, to collect data for reliability statistics or future lifetime extension and to plan inspection and maintenance.

Certain steps, such as oil and grease sampling and analysis, are included here because they provide valuable evidence of current health or condition of the assets. This is despite any expectations that these activities may usually be categorised as part of inspection.

The condition monitoring may provide further input to the selected risk assessment methods, which in term can lead to improvements in the inspection and maintenance scheme.

Step 5: Health and safety review

Although as stated earlier, guidance is not provided in this technical specification regarding aspects of design or management relating to health, safety and the environment, it is useful to review the HSE records kept for a particular wind farm, providing evidence of compliance with local requirements and the process of managing risks to technicians, visitors, third parties and the environment. This HSE review is described in Clause 9 (*Health and safety information*) and should comprise part of the review of wind farm historical and future operational management. It will contribute evidence as to whether or not it would be technically safe for personnel to continue on-site activities over an extended period.

Step 6: Analytical assessments of RUL

Step 6 includes analytical methods for determining the remaining useful life of the asset. Such methods range from simple scaled estimates to absolute assessments. The first methodology relies on scaling functions or ratios (applied to damage equivalent loads), derived firstly using parameters used for design and secondly those for the specific operational site. This may be appropriate when available models, assumptions or parameters are not well known or capable of being validated. In contrast, the second approach is only suitable for situations, characteristics, operational states, machines and models which may be defined accurately. Such methods are described in Clause 10. Furthermore, analytical assessments shall always be accompanied by estimates of uncertainty and accuracy, covering input data and the calculation model itself. The result of the accuracy assessment should serve as an input to the risk assessment process.

Also described are probabilistic models and models derived from measured loads. The latter serve to take full advantage of historical data to improve RUL estimates for specific components and structures. It is anticipated the results of these desktop studies provide a better basis for the assessment of risks, as described in Step 2, than a strategy based on inspection and maintenance alone.

Suggestions for methods of analytical RUL estimates can be found in Clause 10 (*Analytical assessments of turbine lifetime*).

Developing the list of steps in Figure 5 and indicating how to increase confidence in the RUL estimate is shown in Figure 6. The confidence level plotted on the horizontal axis is qualitative. As the cycle is repeated, more knowledge accrues, serving to increase levels of certainty further. Naturally, this could be counteracted over time by any accumulated uncertainty, associated, for example, with models of structural loading. Such effects are described in Clause 10 (*Analytical assessments of turbine lifetime*).

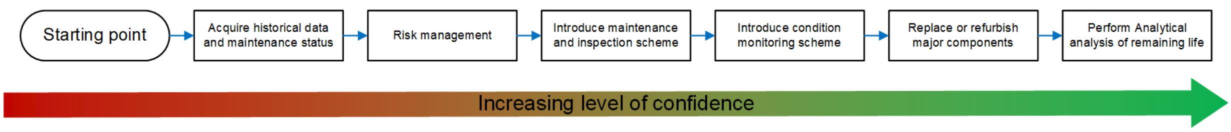

Figure 6: Increase level of confidence, gradually by applying the methods

5 Data management, requirements and uncertainty

5.1 Preamble

This clause defines the processes surrounding data capture and management that describe “best practice” for through-life management and which, if followed, will maximise the value of data and their contribution to general operational analysis and specifically any assessment of remaining useful life.

Assets shall be identified through a designation system which assigns unique identification relating to physical and virtual assets. Such a designation system shall follow accepted and consistent industry standards.

Note that clear guidance is provided in other documents such as the Reference Designation System for Power Plants (RDS-PP [I.20]).

Fundamental to any assessment of failure risk or reliability of wind turbines throughout operation are uncertainty and availability of data. Input parameters for models of loads and RUL are derived from these data during development and operational phases. Throughout its operational life, the basis for assessing the risk of failure of a wind turbine is knowledge about the original design and how the previous operation and maintenance has affected the remaining life. In addition, the meteorological conditions observed during the operation of the wind turbine are of paramount importance, as they directly affect the likely life of the turbine.

When data or information are scarce or the uncertainty in the data is high, the corresponding uncertainty in the assessment outcome is likely also to be high, whereas when comprehensive data of low uncertainty is available, confidence in risk estimates can be maximised. Also contributing to the overall uncertainty, are intrinsic characteristics of the assessment methods including the underlying physics of failure.

This Clause on management, requirements and uncertainty covers the data and information that may be available from a number of sources, including design, site assessment, installation, operational history, instrumentation/condition monitoring, modification logs, maintenance/field history and inspection records. It also covers the management of such data throughout the lifetime of the wind turbine.

Note that not all data are captured comprehensively, during the lifetime of each individual turbine. Strategies exist to address this issue, based on scrutiny of data from turbines of similar design, site conditions, maintenance history and operational philosophy. Implementing such strategies may enable estimates of missing data, either relating to specific events or periods of time or to gain general insights gained regarding condition, reliability or optimum frequency of inspection or maintenance. It shall be further noted that wake effects may result in turbines, which are not directly adjacent to each other, being subject to similar fatigue loads and estimates of RUL.

5.2 Data management

Management is the process by which data and information collected before and during the wind farm operation are handled so that they can be made available for any decision-making by stakeholders concerning the safety and reliability of each wind turbine. The process principally consists of the following elements, that are embodied, for example, in ISO 8000: *Acquisition of data and information* [I.19]:

- Validation and calibration
- Storage
- Protection
- Processing

Adoption of standards such as ISO 8000 [I.19] facilitates portability and maximises quality of the information (both qualitative and quantitative), ensuring it is fit for its intended purpose in operations, decision-making and planning. Instrumentation calibration would be covered by standards such as ISO 9001 [I.17] and ISO 17025 [N.36], with traceability back to national calibration laboratories (such as UKAS, NIST or other international equivalents) that would be accredited according to ISO 17025 [N.36]. Uncertainties should be estimated as a result of any data processing undertaken.

5.3 Data and information definition

There are two possible classes of data/information that will be used in through-life management (TLM) and lifetime extension (LTE).

- Dynamic data that are likely to change rapidly during operation (for example, wind speed, shaft speed, angle, cycles, frequency, temperature, etc) and condition monitoring (CM) data (for example, vibration, ferrous particles [PPM], oil analysis, corrosion depth, crack depth). These are likely to arise from condition monitoring systems (CMS) and require interpretation for diagnosis or prognosis, for which both data uncertainty and model uncertainty must be assessed. For measured data, uncertainty shall be estimated according to ISO/IEC Guide 98-3 [N.27] which states that assessment of uncertainty for measured data is mandatory.
- Static data or information (for example, inspection reports, manuals, drawings, procedures or others relevant to the assessment) for which uncertainty is not relevant – these do not have uncertainty but tolerances (thicknesses, diameters, rated power,

weights, position of centre of gravity, inertia). Tolerances may induce variance into the assessment by altering the strength or the dynamic loads.

Account will be taken of both classes of variability described above when quantifying uncertainties intrinsic in the assessment of historic, current or future asset health, by any method. Data uncertainties and tolerances (as well as assessment method uncertainties) will be included in the overall uncertainty stated alongside the conclusions of the assessment.

CM data will be used for TLM and LTE, partly as a check on the accuracy of assessment methods (for example, confirming predicted crack or corrosion depth) and partly to monitor the rate of deterioration of components whose life cannot be predicted (for example, inaccessible structural components, bearings and gears). It would also be used as a trigger for inspection interventions, such as boroscopy or NDE.

Static data or information provide the background that defines the wind turbine design and condition. These include dimensions and specifications of components, for example, Clause thicknesses, tensile/fatigue strength, damping ratios, component mass and centres of mass. As such, they include data that may have uncertainty, arising from any assumptions made, especially if reverse engineering is used. Information also includes procedures and manuals that are used to define good practices for TLM.

5.4 Data/information sources

5.4.1 Design information

Many documents and data sources are essential for any analysis and may be available from the OEM. These documents include, but are not limited to, the following.

- Design codes and methods
- Wind turbine technical information (see requirements for the scope of wind turbine type certification in the IECRE-OD-501 series [N.23] and also IEC 61400-1 [N.1] Chapter 13 as a strict minimum but with the following additions):
  – manufacturer and type
  – specifications for components in the primary load path
  – wind class
  – design life
- Approval documents and supporting information or calculations
  – type certificate
  – site-specific turbine suitability assessment (including site specific assessed life)
- Design power histogram (hours operated within defined power bands)
- Power curve (turbine, SCADA and power converter software)
- Site-specific installation details (for example, raw wind data)
- Wind farm layout
  – wind turbine coordinates
  – roughness and terrain maps
  – meteorological mast positions and configuration, including mast geometry, instruments, calibration certificates of the sensors
  – neighbouring wind turbine locations and configuration
- Design FMECA for systems and components
- Design calculations
- System and component specifications
- Schematic arrangement drawings

- Anticipated numbers of starts, stops and low-voltage events, including emergency stops
- Maintenance procedures and philosophy, including time and condition (for example, repair on failure, repair at fixed service intervals, RBI, RCM)
- Site calibration and power curve measurements (if available)
- Energy yield estimates
- Execution of foundations, WTG installation and commissioning documents, reporting details of all specific deviations from anticipated conditions or execution of tasks
- Acceptance test results

These documents should confirm that design guidelines and standards valid at the time have been fulfilled.

5.4.2 Meteorological data

During wind farm development, a temporary or permanent meteorological mast may have been installed to measure wind conditions as input data to wind turbine selection and design. Met masts typically have one or more anemometers and wind direction vanes. Some may have barometers, temperature and relative humidity sensors. Ground-based LiDAR, SoDAR or others equivalent equipment may also be used.

Wind measurements should be made at 10-minute intervals (ideally from several instruments on different masts, at a few heights, including hub height) for a period of at least 6 months before wind farm installation. But where seasonal variations contribute significantly to the wind conditions, the monitoring period should be at least 12 months to include these effects. Data would include summary statistics of wind speed, wind direction, temperature and atmospheric pressure (for all quantities, at least average, minimum, maximum and standard deviation).

Provided it can be demonstrated as suitable, data collected during wind farm development (and during subsequent operation where available) may be used in TLM and LTE assessments to compare design assumptions with actual site conditions.

It may be necessary to carry out additional measurements to support LTE assessments in the case of lack or absence of wind data of sufficient scope or pre-construction site data. Suitable instruments would include those mounted on a temporary meteorological mast, LiDAR, SoDAR and anemometers or devices on the nacelle and hub. In every case, appropriate calibration and corrections must be made in accordance with ISO 17025 [N.36]. Measurements may be made from temporary met masts of wind speed, direction, air density and temperature to derive the wind rose, Weibull distribution, average vertical shear, ambient turbulence intensity, yaw misalignment, up-flow and horizontal wind veer.

5.4.3 Wind data from nacelle

Nacelle-mounted instruments are capable of measuring wind speed and direction, although a lower level of confidence must be associated with measurements due to significant flow disturbances from the operational rotor. Alternative third-party equipment can be used for permanent and more accurate measurements according to IEC 61400-12-2 [N.6] (for example, forward-facing LiDAR or spinner anemometers). To minimise the uncertainty associated with the data collected, methods defined in IEC 61400-12-2 [N.6] may be applied. Averaging and gust data can be generated according to WMO guidelines [N.33], typically with a rolling average over a few minutes and gusts over a few seconds. Some anemometers also include temperature sensors. Crude estimates of turbulence intensity may be made by nacelle-mounted instruments, but more accurate estimates will be obtained from a met mast (or spinner anemometry, LIDAR). The suitability of met mast measurements depends on the complexity of the site and accuracy of the model used to transform data collected by instruments on the mast to the anticipated conditions at the location of each turbine. The total approach shall be verified and evidence provided to demonstrate sufficient accuracy or conservatism.

Data recorded over operational life may be used to compare design assumptions with actual site conditions.

Using such data, a RUL assessment shall be undertaken in alignment with the philosophy described in the Clause covering the assessment of a wind turbine for site specific conditions of IEC 61400-1 [N.1].

5.4.4 Extreme site conditions

If it is known that there have been changes in conditions at the site likely to have affected the statistics of extreme events, the assessment of structural integrity to extreme site conditions may be made through comparison of the statistical distributions used prior to construction with those observed at the site at the time of the RUL assessment. Examples may include the following:

- Climatic changes
- Improved data and statistical models
- Exposure period

The same approaches shall be taken for the assessment of structural integrity as used prior to construction. Details are given in the relevant design standard in the IEC 61400 series and normative references (for example, [N.1] and [N.3]).

Clause 5.4.4 shall be implemented if it is known that there have been changes in conditions at the site likely to have affected the statistics of extreme events and additionally if appropriate models may be constructed to enable structural reserve margins to be calculated, using an absolute approach. The assumptions used prior to construction may be evaluated afresh, based on new evidence.

5.4.5 SCADA data

IEC 61400-25-1 [N.8] and IEC 61400-25-2 [N.9] define the parameters to be recorded by SCADA systems. However, few are mandatory and most are optional. Table 3 of IEC 61400-25-1 [N.8] shows the information categories. Of most interest to TLM and LTE are analogue, statistical and historical information.

It is highly recommended to keep records of at least the following quantities.

- Working hours
- Alarm, warning and operational logs
- Nacelle orientation
- Wind direction at nacelle wind vane
- Temperature of main components (average, maximum, minimum).

Most processed data are available at high sampling rates but only recorded as 10-minute statistics, according to the minimum requirements of the IEC standards. It is recommended to store data in the following list at higher frequency. It should be stated, with justification what frequency is used:

- Electrical variables from converter, transformer and generator (average, maximum, minimum)
- Blade load sensor measurements, if available (average, maximum, minimum)
- Active power output (average, maximum, minimum)
- Reactive power output (average, maximum, minimum)
- Wind speed at nacelle anemometer (average, maximum, minimum)
- Nacelle orientation
- Wind direction at nacelle wind vane
- Rotor and generator rotational speed (average, maximum, minimum)
- Pitch angle for each blade.

For older wind turbines, there may be fewer than a hundred logged channels, with several hundred in wind turbines designed more recently.

A wind power plant comprises several components which may be modelled as individual devices. According to Figure 3 of IEC 61400-25-2 [N.9], a system of logical nodes is defined. Mandatory/optional data are defined in Table 2 of IEC 61400-25-2 [N.9], indicating that most are optional.

5.4.6 Instrumentation

Instrumentation may be permanently mounted (for example, SCADA, SHMD or CMD supplied by the manufacturer and built into the equipment) or mounted temporarily as part of a short-term measurement campaign (for example, accelerometers or strain gauges). In addition to strain gauges, other sensors are available in industry to measure strains.

Instrumentation can be categorised according to the system being monitored, for example, rotor system, main shaft, gearbox, generator, converter, HV transformer, turbine lubrication system, yaw system, hydraulic system, control and protection systems and ancillary equipment.

5.4.7 Operational experience

Data may be gathered over operational lifetime. These data include, but are not limited to, the list given in Annex C (*Physical Inspections*).

Any modifications of the original OEM specification shall be logged for each individual wind turbine (such as closed-loop control software, alarm thresholds, settings, SCADA versions, associated power curves, upgraded, replaced or refurbished components, add-ons). These logs shall include technical justification for such modifications as these will have an impact on life, safety and reliability. Any such modifications shall be logged through the applicable change management process, for example that developed and specified in accordance with ISO 9001 [I.17].

5.4.8 Maintenance and field history

Maintenance may be carried out under warranty, OEM maintenance contract, operator in-house teams or third-party ISP. In each case, documented history should be maintained for each turbine covering both planned and unplanned interventions.

The maintenance history should cover, amongst others, maintenance spare parts consumed (with detailed information about brand and type in addition to the OEM SAP code), lubricant top-ups/exchanges, WTG component retrofit/upgrades and software upgrades for individual wind turbines. Also covered should be any failures, failure investigations, failure modes and root cause analyses (RCA).

Where common failures occur across a wind farm (or farms), appropriate statistical analysis should be undertaken to develop statistical models for predicting the likelihood of future failures, for example, fitting statistical distributions to data, such as Weibull or Weibayes. This will assist in maintenance planning and spares provisioning. However, models may not be statistically valid where case numbers are limited, relevant to a particular site.

5.4.9 Inspection history

Inspection records and reports should be held for individual wind turbines. Inspection can cover the following aspects:

- Structural integrity (for example, dye penetrant or NDE for detection of cracks)
- Boroscopy (for example, main bearing, gearbox bearings, gears)
- Dimensional (for example, wear, free movement, play, backlash)
- Visual (for example, leakage, overheating, loose/missing/fractured bolts, corrosion, dents, stress raisers)
- Bolt tension (for example, re-torquing)
- Grease and oil sample analyses

Any inspection report must be accompanied by all the raw information collected. Examples would be full descriptive records, including all the pictures in original digital format, videos for internal blade inspection with drones or crawlers, full surface picture record for external blade inspections. The objective is to enable subsequent review and independent assessment of the raw data.

5.5 Data requirements for components in the primary load path

The data requirements for components in the primary load path are described in Annex B of this Technical Specification.

When data and information are not available, for example, in aged wind turbines, it may be necessary to acquire new wind data (for example, average, gust, turbulence, shear, veer, inclination) for one or more turbines in a wind farm over a period of several months and ideally over a full season.

This may be supplemented by suitable instrumentation of blades, tower and foundation with strain sensors or accelerometers to correlate wind data with stresses and deflections. Using prior knowledge of fatigue hot spots, the objective would be to develop histograms of stress amplitude against cycles for calculation of accumulated fatigue life (fatigue limit state). Additionally, an inspection regime may be implemented.

Note that the capture matrix in IEC 61400-13 [N.7] may be used to define measured load cases. Furthermore IEC 61400-13 [N.7] provides guidelines regarding recommended instrumentation for load measurements

SCADA data (most likely at 10-minute averages) are unlikely to be of sufficient resolution to identify substantial/significant load cases. An example would be the timing, duration and severity of an emergency braking event, occurring over a few seconds. To identify such an event would require high resolution load monitoring (vibration analysis would need a sample rate of >50Hz). If higher frequency for data collection is needed, it should be defined and justified. For the purposes of assessing SSEL, a measurement campaign with high resolution data may be carried out to reduce the uncertainty of the assessment. This is particularly important for components in the primary load path (and others in the drive train) where short duration load and vibration cases are critical.

Alternatively, relevant insights may be inferred from similar turbines in similar wind conditions, possibly through scaling data. Scaling methodology and assumptions shall be verified.

In addition, to perform load calculations, there are a number of parameters relating to design that are desirable including but not limited to the following (see Annex B for more exhaustive listing):

- Blade characteristics (aerodynamic, structural and geometric)
- Blade frequencies
- Blade damping
- Hub characteristics (structural and geometric)
- Nacelle characteristics (structural, geometric and inertial properties)
- Nacelle tilt angle and drag
- Drive train stiffness, damping and eigen frequencies
- Gear box ratio
- Tower characteristics (structural and geometric)
- Tower frequencies
- Tower damping
- Foundation structural and geometric characteristics
- Design evaluation reports (third party)
- Probabilistic analysis report
- Control system parameters.

This list is not limited depending upon existing and future designs. For example, main bearing clearances or preload and pitch bearing clearances that will evolve with wear and may change the dynamic behaviour of the drive train.

This approach is also recommended to decrease uncertainty in the outcome of assessment methodologies by improving the quality of existing data and information.

Note that methodologies for performing load calculations are described in Clause 10, covering analytical assessments of turbine lifetime

5.6 Data uncertainty

ISO/IEC Guide 98-3 [N.27] gives the clearest and most appropriate description of the treatment of data uncertainty. Compliance with this TS requires the assessment of uncertainties in measured data.

For a reported value, the uncertainty defines a range of values within which the true value is expected to lie. Estimates of uncertainty should therefore incorporate errors from all effects, including those which are systematic and random. The result of any physical measurement is a numerical value and the degree of uncertainty associated with the estimated value, within a specified level of confidence. For example, wind speed could be recorded as 20±0.2m/s.

The following terms are relevant to a comprehensive understanding of uncertainty.

- True or reference value (traceable to a reference standard)
- Accuracy – closeness of agreement between measured and true value
- Error – difference between a measurement and the true value
- Systematic error would shift the measurements in a predictable manner
- Random error is a component of total error but is related to an unpredictable manner
- Trueness is the closeness of agreement of the average measured value to the accepted value
- Precision is a measure of how well a measurement can be made without reference to a true value
- Repeatability is a measure of the precision when the same equipment is used by the same operator on identical specimens
- Specific treatment of the signal before display and recording (for example, opaque and alterable conversion formulas for nacelle anemometer measurements)

IEC 61400-12-1 [N.5] and IEC 61400-12-2 [N.6] cover the determination of wind turbine performance parameters in order to estimate annual energy production (AEP) and conformance to design specification. In terms of wind speed, specifications are given for the installation of met masts and calibration of anemometers. The difference between the regression lines upon calibration and re-calibration shall be ±0.1m/s over the range 6 to 12m/s.

Uncertainty in the measurement of wind speed derives from a number of sources, including anemometer calibration, mounting effects, flow distortion due to terrain, operational characteristics of the anemometer and systems for data acquisition, storage and retrieval. IEC 61400-12-1 [N.5] defines the method by which the total uncertainty is derived from individual elements.

Whilst the standard also covers air temperature and pressure measurements, it should be expected that similar methods would be used to determine the uncertainties of other measurements such as turbulence intensity and vertical shear.

To account for uncertainties of all other data and information in a similar way, please refer to the examples in Annex D.

5.7 Classification of uncertainty

In order to describe the uncertainty of data, a system of classification based upon Levels 1 to 4 is recommended. Based upon an assessment of the coefficient of variance (the ratio of the standard deviation to the mean), the data uncertainty level may be determined at the 95% confidence level according to Table 2Table 2.

Table 2 – Classification of uncertainty

COV (SD/mean)	0.05	0.1	0.15	0.2	0.25	0.3
Mean ±1 SD (68.2%)	5	10	15	20	25	30
Mean ±2 SD (95%)	10	20	30	40	50	60
Mean ±3 SD (99.7%)	15	30	45	60	75	90
Data uncertainty level	1	2	3	4		
95% confidence	5 - 10%	10 - 20%	20 - 30%	> 30%		

5.8 Data requirements for new wind farms

For new wind farms, the user of this technical specification should refer to Annex B which defines the data/information requirements for each level of assessment model. The use of particular data is strongly recommended, even fundamental to particular assessments, calculations or estimates. Consequently, the accuracy of RUL estimates depends on which data/information are available during site assessment and design, according to the type of assessment made, the models and the associated uncertainty level. Assessment philosophies include physical inspection only, relative loading and absolute loading (deterministic, probabilistic or measurement-driven). These are described in Clauses 7 and 10.

6 Risk management process

6.1 General approach

A risk assessment shall first be performed in all cases in order to confirm structural integrity, safety and as a precursor to turbine RUL calculation. One of the objectives of a risk assessment is to provide understanding of the risk level of the asset, and whether actions, preventative or mitigatory, are required to achieve an acceptable risk level. A risk assessment typically would result in the development of a prioritised list of risks, failure modes and associated components. All equipment and components of the wind farm are within scope. An iterative risk assessment methodology is presented in Annex F, as an example, with the following objectives:

- The intention is for the risk assessment methodology to be suitable to indicate the current status of the components and systems in question (or their health). The primary purpose is to ascertain minimum integrity of the primary structure to ensure the safety of personnel working at the wind farm and third parties
- Relative assessments may be made by first establishing a benchmark for the wind farm using the same methodology as was applied prior to construction, evaluating risk in the same way as the design team and quantifying changes over time
- Absolute assessments shall always comply with current design requirements and governing international standards, especially where increased safety is required relative to the state of the art at the time the design was originally assessed
- The risk ranking shall be kept up-to-date. Risk profiles may be updated periodically, taking into account accurate current operational information, using the same methodology. In this way changes may be identified and trends established
- Ranking components and modes of failure would enable priority to be given to those with the highest risk, enabling targeting, not only of analysis but also monitoring, measurements campaigns, repairs and replacement of parts
- Risk rankings may be re-evaluated periodically, taking into account data regarding failure modes, probabilities of occurrence or severity of the failure specific to the operational site. These rankings may be used for maintenance task planning and strategic decisions about monitoring, spare parts, training personnel and tools.

This final application of the methodology enables estimates of the probability that, at a future point in time, the structural integrity of the system will be sufficient, safety and protection functions will be fully operational. Figure 7 shows an iterative sequence for risk assessments.

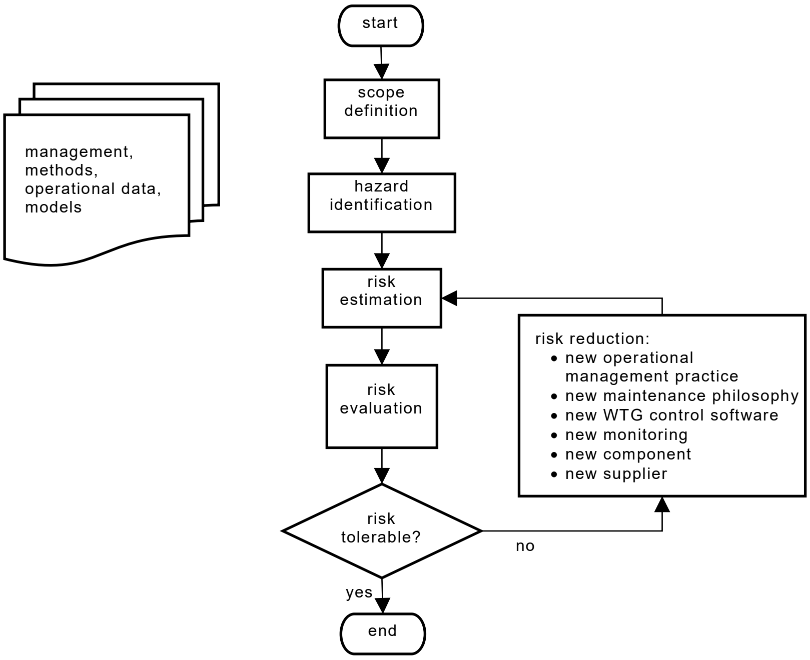

Figure 7: Iterative sequence in general risk assessment procedures (based on IEC 31010:2019 [I.16])

The selection of the method should be informed by the complexity of the issues identified and the severity of the outcomes or consequences. Particular attention will be given to assessing the safety and structural integrity of the turbine. For example, risks which are simpler, rarer or have less severe consequences may only justify a simple method, whereas more complex, higher risk situations may require more detailed, semi-quantified risk analysis.

This Technical Specification does not identify a specific normative standard defining how to conduct the risk assessment. The over-arching approach recommended is based on ISO 31000:2018 [I.15], which provides principles, frameworks and a process for managing risk.

Details of specific techniques that may be applied are described in [I.16]. Standards that may be suitable to assist the reader in conducting a suitable level of risk assessment include, but are not limited to [N.16], [I.14] and [N.14].

Note that users of this TS may also be assisted by the use of relevant management systems standards such as ISO 9001:2015 - Quality management systems [I.17] or ISO 45001:2018 - Occupational health and safety management systems [I.18] or ISO 55000:2014 - Asset management [I.3]. Each applies a sequence indicated by the key words Plan – Do – Check – Act, which could be helpful in managing the overarching risk assessment methodology.

As a minimum, the selected risk assessment method shall be able to estimate the following, with suitable confidence limits stated:

- Numerical values for risk priority, either absolute or relative allowing comparison of all items comprising the system under scrutiny (for example, the wind turbine or component)
- Evaluation of risk priority number (RPN), for example, as prescribed in [N.16], which is the product of the properties of each mode of failure, defined in Table 3.

Table 3 – Key properties of failure mode and components of a risk priority number

Severity	severity of outcomes (for example, catastrophic structural failure)
Occurrence	likelihood or probability of the incident occurring
Detectability	possibility that the failure mode goes undetected, potentially due to having inadequate data or other indications to detect failure modes in sufficient time to allow action to be taken to prevent catastrophic failure
Risk Priority Number (RPN) = Severity (S) × Occurrence (O) × Detectability (D)	

Informative Annex F provides an indicative worked example of the application of this approach using the methodology set out in IEC 60812 [N.16].

Alternative, or proprietary risk assessment methods are acceptable, but the process should at least align with the philosophy, assumptions and approaches set out in this TS.

6.2 Scope of risk assessment

The focus of risk assessment should be the uncertainty related to the integrity of structural or major components, assessed for the specific site. Specific information that is likely to inform the risk assessment process includes but is not limited to the following:

- Commissioned/as built design information, for example, as listed below:
  - as built plans/designs
  - technical files
  - site plans etc
- Maintenance and inspection information, focusing on structural elements and connections comprising the primary load path
- Operating history, particularly considering any events that may indicate abnormal loadings or potential structural deficiencies
- Condition monitoring data, to the extent that they relate to components in the primary load path
- Analytical estimates of RUL
- Events, incidents and failures experienced at the site and in the fleet of similar turbines
- Relevant health and safety information (see Annex A)

An iterative approach may be taken to establish the scope. Initially the scope shall comprise the whole wind farm but may rely on qualitative assessments of risk. Once all top-level systems in the wind farm have been ranked, further detail may be provided for the highest risk items. Through subsequent iterations, the scope may be reduced in a rational manner. After several iterations, the highest-risk items may be assessed quantitatively, using best available operational data.

6.3 Life extension risk assessment

Additional or more detailed assessment may be necessary considering, for example, the following items:

- Changes to the design requirements, factors of safety or probability of failure, described in the latest editions of the IEC-61400 series of standards and normative references
- Changes to local legislation (for example, health and safety, planning) or consenting rules
- Changes to local site conditions (for example, new neighbouring forestry, infrastructure, wind farms, housing, electrical grid integrity)
- Changes to local environmental parameters (for example, flooding, wind conditions) in comparison with the turbine type class

- Aspects of machine or other equipment design which, while deemed tolerable when first installed, now present a level of risk that significantly exceeds an acceptable threshold.

Irrespective of any commercial or regulatory requirements, the decision to proceed with any extended operation shall be subject to confirmation by relevant stakeholders that risks relating to structural safety are acceptable.

7 Wind farm operation, maintenance and inspections

For each turbine, the name plate shall comply with the requirements of IEC 61400-1, Clause 5.5 [N.1] if applicable at the time of turbine erection. Similarly, the turbine type class shall be indicated as specified in Clause 6.2 of same standard [N.1], including turbine design life and any special conditions (for example, relating to Class S turbines). Where the class is site-specific, further evidence shall be provided (for example, measurement campaign, model results, environmental simulations). A valid type certificate or equivalent for the turbine should be available (as an example, wind farm project certification may have been updated after the expiry of the wind turbine type certificate).

7.1 Replacement of structural or major components

The definition of which constitute major components should be at least those listed in the type certificate (for example, as designed in IECRE OD-501 [N.23]).

Evidence of structural component repair, refurbishment or replacement shall be collected where available and recorded in a wind turbine change log.

- Manufacturer/series/model
- Date replaced
- New/used or refurbished

RUL assessments of structural components shall be undertaken. Depending on the asset management strategy, such assessments may be carried out for major components as well. such assessments can be independently reviewed or certified. For a wind turbine being dismantled, reconditioned and re-installed at a new site, the assessment of RUL may cover specific components or the entire wind turbine.

If any replacement components are not covered by the original design type certificate or equivalent for the turbine (for example, as certified in accordance with IEC 61400-1 [N.1] or IEC 61400-2 [N.2] in the case of small wind turbines or IEC 61400-3-1 [N.3] or IEC 61400-3-2 [N.38] for offshore wind turbines), approval of its suitability with regards to the design assumptions should be provided, ideally by the OEM. If such agreement from the OEM is not possible, an impact assessment should be undertaken and calculations of structural integrity completed for components in the primary load path, building on the recommendations detailed in Clauses 5.6, 5.7 and 6.

If the OEM no longer exists, then assessment or approval by suitably qualified parties may be substituted.

Documentation of component replacements may include WTI (Wind Turbine Improvement) or WTR (Wind Turbine Retrofit) reports, explaining the reasons for such modifications. Examples would include performance improvement, change of supplier or safety retrofit.

7.2 Operation and maintenance

Operation, commissioning and maintenance of wind turbines shall be undertaken in accordance with the version of IEC 61400-1 [N.1] (or IEC 61400-2 [N.2] in the case of small wind turbines) which was applicable at the time of design.

Types of maintenance tasks are set out in Figure 3 of IEC 60300-3-11 [N.14]. Following best practice and a philosophy of continuous improvement, the owner or operator would be expected to replace corrective with preventative maintenance regimes. Consequently, the level and quality of data used for RUL assessments would be also expected to improve.

Assessment of structures and collection of operational data shall, as a minimum, cover, where possible, the following:

- All mechanical and electrical components and assemblies, related to the primary load path of the wind turbine
- All components related to the safety functions, control and protection systems.

Operational data about the wind turbine, that may be collected and reviewed throughout life and at the end of Design Life are described in Annex B.

Information that is recorded throughout the operating life may be used to modify the assumptions used in the assessment of RUL. The use of an asset management system such as set out in ISO 55000 2014 [I.3] is recommended.

The information collected can be associated with a single turbine and may also be interpreted as representing several or all turbines in a wind farm. Sufficient documentation of site-specific operations should be available to justify any changes to the assumed operational strategy and the site characteristics made in the original machine site-suitability assessments (as detailed in IEC 61400-1 [N.1] or IEC 61400-2 [N.2]) used as the basis for estimating an updated RUL. This will ensure that any information derived from historical records is suitable for assessment of future operation.

Records of inspections, assessments and reports should be made available for review (for example, as part of technical due diligence) if there are any changes of wind farm ownership or responsibility for operation.

Operation of wind turbines shall adhere to any project specific operational requirements resulting from the site climatic conditions, to include sector management or other operational limitations with the purpose of managing loading. In the event there has been a material change in site climatic conditions, the operational requirements shall be revisited. Records shall be kept of any changes to modes of operation and significant events.

The most up-to-date service manuals should be made available by the OEM. However, in practice the operation and maintenance manuals used by the operator may be based on previous OEM versions and updates may not have been provided. Reviews may be conducted of all available revisions, including different versions applied over the operational life of the wind turbine to provide context for historical events and changes in operational practices. Further information can be found in Figure 2 of BS EN [ISO] 60300-3-11 2009 [N.14] which sets out how a maintenance programme can change over the operating life of an asset.

Historic operational knowledge about the wind turbine platform may be considered (for example, failure rates, failure modes, locations of damage detected) in order to look for evidence of serial early wear or failure on the wind farm that can be attributed to component quality or manufacturing issues.

If any replacement components are not covered by the original design type certificate (as certified in accordance with IEC 61400-1 [N.1] or IEC 61400-2 [N.2] in the case of small wind turbines or IEC 61400-3-1 [N.3] or IEC 61400-3-2 [N.38] for offshore wind turbines), approval of its suitability with regards to the design assumptions should be provided, ideally by the OEM. If such agreement from the OEM is not possible, an impact assessment should be undertaken and calculations of structural integrity completed for components in the primary load path, building on the recommendations detailed in Clauses 5.6, 5.7 and 6. Such an assessment may, e.g., be based on a comparative analysis of design margins or material resistances.

If the OEM no longer exists, then assessment or approval by suitably qualified parties may be substituted.

After an inspection has been completed, or as a result of data or conclusions from CMS, SCADA systems, other measurements or analytical assessments, a revised operation and maintenance schedule with new frequencies or types of inspection may also be defined. Principles of risk-based inspection (RBI) [N.13] or reliability-centred maintenance (RCM) [N.14] may be applied.

Any uncertainty about component RUL can be removed, limited or managed by replacement of the component, application of condition monitoring techniques or increasing the frequency and scope of inspection.

7.3 Physical inspections

This Clause concentrates on the requirements for physical inspection. Firstly, highly recommended inspections, to comply with the requirements of this document, under ideal circumstances and secondly, informative inspections, which if performed, will add value and quality to the assessment of RUL whilst also reducing the uncertainty of the current and future condition of the relevant component.

Examples of inspection tasks would include turbine visits for the purposes of non-destructive evaluation and testing of structural components (for example, at specific locations such as welds or previously identified hot spot locations in castings or forgings), collection of oil or grease samples, alignment of components, thermographic or ultrasonic investigations of sub-surface structural integrity.

Items that primarily relate to personal health and safety are outside the scope of this technical specification. However, increased confidence in the management of the major components can be provided by evidence of regular, consistent, comprehensive health and safety inspections. Supporting records can provide valuable information and help inform risk-based decisions. These include the following:

- Clearly defined Health and Safety Management System to include evidence of Statutory Inspections and full written scheme compliant with regulations. Health and safety inspections (for example, ladders, lifting equipment, fall arrest systems) can provide valuable proxy evidence on how well the wind turbine has been maintained (see Annex A)
- The regulatory and reputational risks associated with a potential serious incident (for example, fatality or serious injury) may demand that suitable health and safety due diligence checks are conducted
- New regulations or updated standards and good practice may identify the need for and opportunities to review and upgrade equipment and systems for control of risks.

Informative Annex A provides an indicative summary of the potential health and safety assessment and inspection checks that may need to be carried out, both during the operations and maintenance phase, but also to assist in life extension assessments.

7.4 Scheduling of physical inspections

Having a considered approach to TLM should ensure a good understanding of the condition of the wind turbine throughout the operational life. Starting as early as possible is recommended, even prior to design or construction so that strategies are developed and communicated clearly to all stakeholders. Far more efficient are designs taking account of operation and inspection than equipment which is intrinsically hard to maintain. Commissioning and hand over to the operations team is clearly important for initiation of the approach to TLM. The guidelines set out below recommend a series of inspections that should be carried out in addition to the scheduled maintenance .

Carrying out the full scope of these inspections provides an owner/operator with an approach to maintain knowledge of the condition of their asset. Where Condition Monitoring Systems (CMS) provide relevant information, data may be used to trigger or replace physical inspections.

It is accepted that it may prove impossible to follow the schedule recommended in these Clauses, for many reasons, including that many components have already started to show signs of wearing out, failing or otherwise approaching or exceeding their safe operational life. If inspections have not been carried out in compliance with the recommendations in this TS, the levels of confidence in safe remaining life may be lower. Procedures for assessing levels of confidence are given in Clause 5.6, Clause 10.3 and Annex F.

In the following Clauses, the term “operational life” has been used as an alternative either to SSAL or SSEL as appropriate, depending on information available and, whether or not, any symptom of failure has been observed.

7.4.1 Early life inspections (15% - 25% through operational life)

This set of inspections is typically carried out as a means of capturing any defects or remedial work required prior to the end of the warranty period. It also presents an opportunity to establish a benchmark for the overall condition of the wind turbine(s) for future reference, to monitor degradation. The recommended inspection scheme includes the items in Annex C.

7.4.2 Mid-life inspections (45% - 55% through operational life)

Following on from the early life inspections, an inspection regime at the mid-point of the operational life may be carried out to provide additional information on degradation rates, highlight any emerging issues and also to form the basis of a sound economic justification for exchanging components preventatively. The recommended inspection scheme includes the items in Annex C.

7.4.3 Life extension preparation inspections (70% - 80% through operational life)

The life extension preparation inspections are a set of recommended inspections that form the basis for the assessment of RUL of the wind turbine components. This set of inspections shall include the main load carrying components. Recommendations for these inspections can be found in Annex Annex A. The principal aim of this set of inspections will be to assess the condition of the components and together with information available from other sources, form an ongoing life extension inspection regime.

The components listed for highly recommended inspection will be included in all regimes, with additional inspections being added based on any findings. This Technical Specification cannot determine what the additional inspections are, as these will be specific to the site; however, current best practice techniques commonly used for assessing and monitoring condition are included in Annex C. It is recommended to use design data from the OEM in listing components for inspection.

A programme of risk-based inspections may then need to continue during the extended period of operation after the end of the project design life. There may be additional inspections/actions identified as a result of carrying out these inspections, and the owner/operator will need to assess and review these findings accordingly.

8 Condition and structural health monitoring

8.1 Purpose

The purpose of this Clause is to provide information, explanation and requirements related to instrumentation, acquisition and analysis techniques of condition monitoring, structural health monitoring (CMS) and corresponding monitoring devices (CMD) installed on a WTG component of a wind farm with reference to this Technical Specification.

Condition Monitoring (CM) is the systematic data collection, recording, monitoring and expertise-based assessment of available parameters associated with an asset that aims to identify the cause(s) of changes in these parameters during monitoring (see Figure 7 below). A well-constructed CMS is both a key process for monitoring optimal conditions, early identification of conditions that may lead to a fault and a failure and a tool for monitoring developing failures. Data may be gathered from different sources including SCADA system, CMDs (sensors), additional measurements or inspections.

Structural Health Monitoring (SHM), as defined in 3.1.20, allows the real time tracking of any number of parameters that are correlated with the state of health of the structure. During through-life management and life extension, these indicators (for example, combined with extent of corrosion, results of inspections, propagation of cracks, tension in bolts) are used to detect changes to that state of health and to predict approaching states of distress or failures. This knowledge allows operators to take preventive measures to keep the plant operating at low stress levels, thereby extending the life of components, and to prevent failures. Common sensors include accelerometers, inclinometers, velocity meters, load cells, and strain sensors. Accelerometers are particularly useful to measure the dynamic response and to detect changes in natural frequencies which are indicative of changes in the structure.

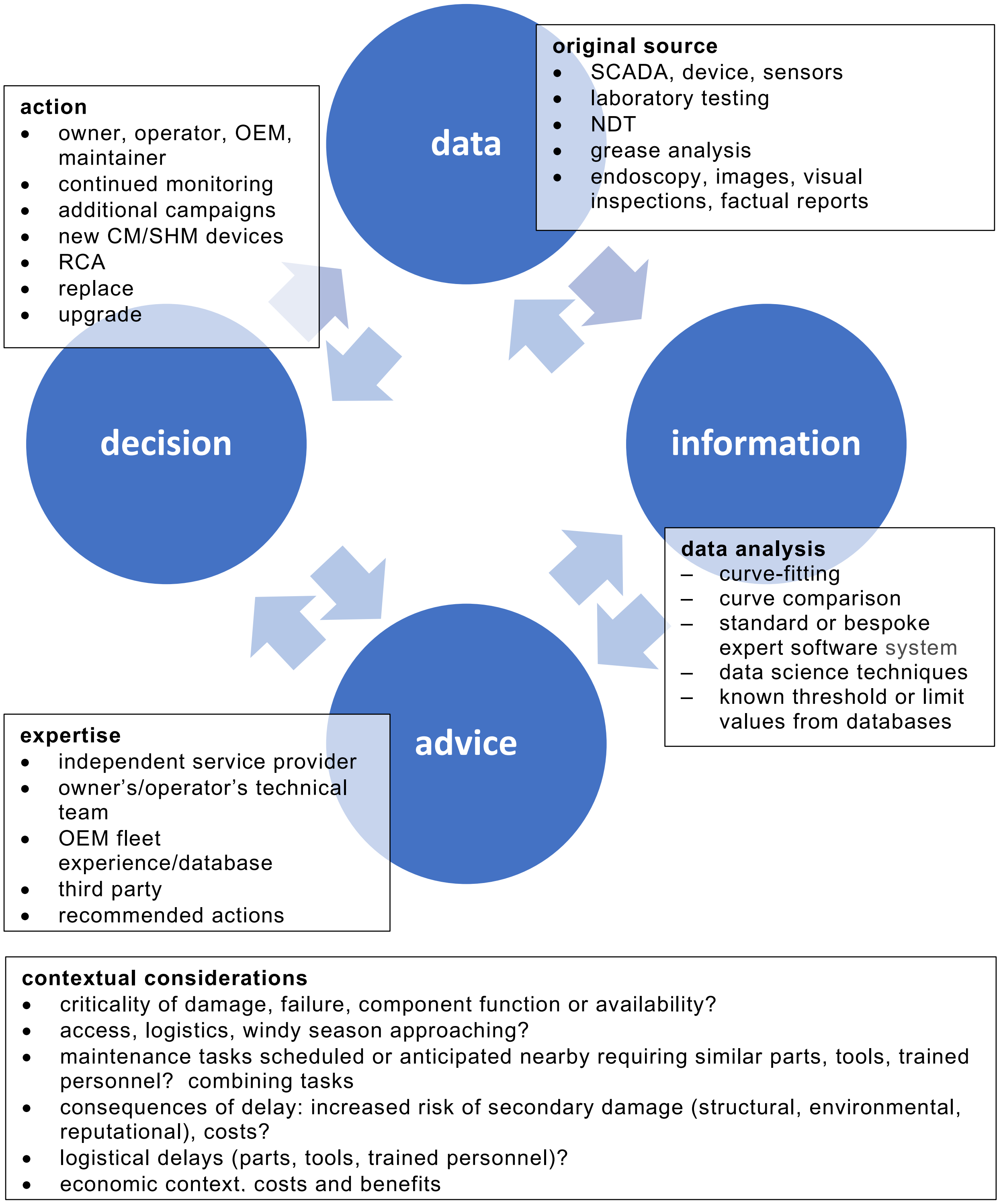

Figure 7: Condition and structural health monitoring management process

An expertise-based, consistent and systematic assessment is an important part of CM. This allows for proper decisions to be made and actions taken to reduce or eliminate the causes of faults thus avoiding or delaying potential future failures.

CM and SHM should be used in the preventative and corrective maintenance approaches. The management process should be defined in a strategic asset management plan (*Organizational Plan*: refer to ISO 55000 series [I.3]). Useful information obtained from WTG CM and SHM executed properly over the operational phase will provide greater confidence in an assessment of lifetime extension and associated costs.

CM and SHM should help in optimization of the reliability of the asset and/or in reduction of failures (safety) and impact of repairs (cost, production loses, risk exposure etc.). CM and SHM allows for early detection and decisions regarding preventative actions for all other turbines in the wind farm or wider fleet.

Through indicative examples, Table 4 distinguishes data from information, advice and decisions.

Table 4 – Example of distinctions between data, information, advice and decision

Data	The temperature of the component is *x*°C
Information	Taking in account all other influential parameters (operation regime, external temperature, etc) and comparing temperature with similar components in similar conditions or neighboring turbines, temperature of this component is too high
Advice	Through application of appropriate expertise, historical experience, further research and project-specific measurements, cross checking with other data, comparing with history and nearby turbines, discussions about the context between key stakeholders (such as wind farm operator and maintenance technicians), the advice from the expert(s) is to change the component during expected forthcoming period of lower winds
Decision	Operator and maintainer have agreed to prepare the spare parts, the tools and plan the operation

8.2 CMD minimum necessary requirement

Note that some systems described here may already be part of the SCADA.

See Annex B.2 for other component data, recording of which is highly recommended along with the expected benefits. A recommended scope for monitoring of rolling element bearings and hydraulic systems is given in Annex E.

8.2.1 Vibration monitoring system (VMS)

Application of vibration monitoring systems is described, in general, in the ISO 13373 series of standards [I.8]. In the case of wind turbines, VMS combined with expertise-based analysis (part of CM) has proved useful for early detection and locating faults, associated with gears and bearings of the complete drivetrain as well as changes to the wind turbine structure. In practice, VMS has successfully detected the faults described in Annex E.5.

The VMS must allow an expert to:

- perform time and frequency domain-based analysis (for example, trending, FFT, envelope, CEPstrum, operation modal analysis),
- bin measurements by operational conditions,
- calculate speed-dependent resampled spectra (i.e a spectrum of a time signal resampled with a synchronous recorded speed depended trigger signal),
- adjust alarm levels of the VMS to improve monitoring of the fault process in the case of early detection of fault.

8.2.2 Temperature monitoring

Temperature of the following components should be monitored and compared with expected operational temperatures:

- Generator bearings, gearbox bearings (when possible) and main bearing(s)

- Gearbox sump
- Lubricant at inlet and outlet of the gearbox
- Generator windings and/or permanent magnets (with redundant sensors shall if repair is not possible)
- Cooling fan motor(s)
- Ambient air inside the nacelle
- Ambient air outside the nacelle (if cooling radiators are outside)
- Generator coolant inlet and outlet (air or water)
- Electrical switchgear
- Power transformer
- Electrical cabinets

8.2.3 Oil and grease wear particle analysis

Monitoring lubricants for development of wear and spalling particles is a well-proven method to ensure the best lubrication conditions, detect deviations and potential faults. Off-line oil and grease condition monitoring and wear particle investigation should be performed on a regular basis at a minimum yearly frequency and following manufacturer recommended sampling procedures for the following components: gearbox, hydraulic systems(s), main bearing(s), yaw bearing and pitch bearings for each turbine.

Although off-line and on-line techniques for monitoring the mechanical and chemical properties of liquid lubricants are now common in wind turbines, methods for measuring and tracking the impurities in grease over time are not defined in any international standards. There is much to learn about the historical operation and the current health of a rotating component. Detailed guidance is outside the scope of this technical specification but, pending availability of a suitable reference, the following aspects should be taken into consideration:

- Grease and oil sampling should be regular (yearly as a minimum) and follow a consistent procedure
- Tests should take account of the metallurgical context of the equipment being lubricated
- Records should be kept alongside every grease or oil sample sent for testing including date and time of sampling, along with other relevant information such as temperature, humidity and time elapsed after turbine became stationary

Oil and/or grease analysis should be performed:

- as a reference, during the first 6 months of operation – ideally as part of the final WTG inspection at commissioning.
- before the end of warranty – on a yearly basis and as a part of an end-of-warranty inspections
- after the end-of-warranty period with intervals based on the results of the previous analysis, but minimum on a yearly basis

Note that most laboratories request brand-new grease or oil samples as a reference.

For early detection, it is highly recommended that the acquired data (laboratory measurement) will be analysed independently with a focus on trends in content of iron, chromium and copper, PQ index and direct reading or analytical Ferrography (see recommended values in Annex E for early detection).

If on-line counters and on-line oil condition monitoring are used, the off-line lab results must be treated as reference because the laboratory equipment is calibrated on a regular basis, which may not the case for on-line equipment.

8.2.4 Site (wind) condition monitoring

It is recommended to document the (wind) site conditions to which a wind turbine is exposed during its operational life since this is indicating how close to the design limits of the turbine type the turbine has been operated. In this respect, and considering the inherent and different uncertainties of the different measurement tools, the following data should be recorded:

- Horizontal wind speed
- Yaw misalignment
- Inflow angle
- Shear
- Veer
- Turbulence intensity
- Air density (temperature and pressure).

Yaw misalignment is not the measured parameter during site wind monitoring, but is normally derived from SCADA data. In order to obtain the most accurate data, it is necessary to retrofit hardware and software, perhaps supplied by a third party.

In addition, it is useful to document changes of the surrounding environment of the site, since this might change over time as well (for example, growing forests, other wind turbines in the neighbourhood, industrial development close by).

For offshore applications, appropriate sea condition measurements should be considered as recommended.

8.3 Structural health and load monitoring

Structural components of the primary load path (for example, blades, tower, foundations) should be monitored with adequate and validated direct or indirect, short- or long-term load monitoring campaigns. These measurements should then be used in data-driven assessments of the RUL of these components with reference to the fatigue limit state (cf. Clause 10.2).

In addition, further limit states and failure modes relevant for structural integrity and turbine operation (for example, serviceability limit state, ultimate limit state) may be monitored continuously making use of damage sensitive indicators. This strategy is commonly referred to as structural health monitoring (SHM).

8.4 Data acquisition

Data produced by any sensor of the CMD or SHM system of the turbine or by any inspection/measurement if used for CM or SHM should be available for the operator/owner.

Data quality from sensor to display should be provided according to ISO Guide 98/3 [N.27] for each signal. The health of the CMD or SHM system (status monitoring) shall be monitored, including, but not limited to, transducers, (where relevant) database availability and usage, and data transfer from CMD Site Server to Central CMD Server. In case of malfunction of any of the monitoring components or services, a warning (system alarm) must be displayed and recorded in the remote control system.

Due to variable regime of wind turbines and influential parameters, a unique threshold on a parameter is not sufficient to detect a deviation. For the purpose of data analysis, it is recommended to use an early warning/early fault detection tool.

8.5 Integration to asset management

As part of CM/SHM, an asset management system (refer to ISO 55000 series) should be established and maintained during the lifetime of the WTG. An asset management system should preserve the raw data available (from the SCADA, from the CMDs, measurements or from the inspections among others) whilst also helping in data analysis and decision making. It should also cover important documentation related to the asset such as: as-built documentation, protocols, legal inspection evidence, reports, test certificates, photos etc (refer to Clause 5 *Data management, requirements and uncertainty*).

Processing and analysis of data may be automated (algorithms) or performed by an expert. In any case, a detection from the CM or SHM shall be recorded and lead to an analysis of the cause with a decision about required actions.

8.5.1 Documentation

An asset management system mentioned in Clause 8.5 should consist of the following minimal scope of CM/SHM documentation:

- The CMD and other data acquisition configuration data sheet
- Technical documentation of the CMD components (instrumentation, hardware brand and type, software versions and updates, network devices, configurations, range, accuracy, tolerances)
- Arrangement drawings, wiring, schematics and communication lines
- Operation and maintenance manuals of the installed components
- Data flow diagrams
- Information about data quality from sensor to display for each signal (sensor type and supplier, range, accuracy, unit, signal attenuation, signal treatment, averaging, conversion formula)
- Alarm generation history (date, time, description, potential causes)

8.5.2 Business procedures

As part of the asset management system supporting CM or SHM, business procedures should be implemented that ensure the following functionality:

- Systematic periodic review and expert assessment of all condition monitoring events
- Review based on the event: creation, registration and categorisation of diagnostic incidents; documenting details in a report listing (as a minimum) diagnosed fault, location, failure mode, severity and recommended maintenance action
- Systematic periodic review and assessment of all CM or SHM errors
- Review based on the system error: creation, registration and categorisation of CMD maintenance incidents; documenting incident details in a report listing (as a minimum) component being monitored, CMD, CMD error, consequence and required maintenance action
- Systematic periodic follow-up on all open incidents
- Feedback from the maintenance organization to CM or SHM expert regarding inspection findings and maintenance actions (from assets with open incidents) regarding diagnostic accuracy
- Systematic periodic verification of all closed incidents where the theoretical diagnosis is compared with findings from the field; incidents are classified as true/false positives/negatives (the purpose of this step is to build a performance track record for the CM or SHM activity and document strengths and points for improvement).

9 Health and safety information

Items that primarily relate to health and safety of personnel (HSE) are outside the scope of this technical specification. However, health and safety inspection and related information can provide valuable information about the turbine historical management context. This will help to quantify risks to inform decisions regarding whether or not to continue or extend operation.

HSE topics include the following:

- Clearly defined Health and Safety Management System to include evidence of Statutory Inspections and full written scheme in terms of regulations. Health and safety inspections (for example, ladders, lifting equipment, fall arrest systems) can provide invaluable proxy evidence on how well the wind turbine has been maintained
- The regulatory and reputation risks associated with a potential serious incident (for example, fatality or serious injury) may demand that suitable health and safety due diligence checks are conducted
- New regulations, updated standards or good practice may identify opportunities to review and upgrade equipment and risk control systems
- Confirmatory records that all retrofits and software updates specified by the OEM have been made, particularly those which address safety incidents.

Informative Annex A provides an indicative summary of the potential health and safety assessment and inspection checks that may need to be carried out both during the operations and maintenance phase but also to assist in life extension assessments.

10 Analytical assessment of turbine lifetime

10.1 Overview

Any analytical assessment of the RUL of a wind turbine and its components in the primary load path needs to be based on structural loads and monitored through established inspection strategies. Several approaches and methods are possible (relative/absolute approaches, simulation-based/data-based approaches). The different approaches are described in Clause 10.2.

One possible, risk-based approach to RUL assessment is described in more detail in Annex D. Other approaches may be followed if they are in line with the requirements stated in this Clause.

All analytical assessments shall be reported in a traceable way.

10.2 Methods to determine loads

Depending on the state of the turbine established in Clause 6 ‘Risk assessment’, RUL estimate may be improved based on one of the methods described in the subsequent Clauses.

It is possible to apply different approaches for different components, e.g., absolute RUL calculation of a site-specific tower design in combination with a relative RUL calculation for the rotor nacelle assembly.

10.2.1 Relative assessment

In a relative assessment, loads under site conditions are compared with loads calculated for the certified design conditions. The loads are calculated with an aero-elastic model. From the load ratio thus obtained the RUL may be derived by using an appropriate damage model (for example, comparison of damage equivalent loads with simple S-N curves). In this approach, design margins are not usually taken into account. These may be taken into account when appropriate design documentation is available. In this case, special attention should be given to the correctness and completeness of the design documentation and the accuracy of the relative assessment. Due to its relative nature, this approach is more insensitive to model inaccuracy than the absolute approach described below. The minimum data requirements for this approach are described in Annex B.

In a relative assessment, the following steps should be performed:

- Use aeroelastic model, optionally validated with load measurements
- Calculate relative RUL using design and site-specific wind conditions
- Adequately estimate RUL uncertainties
- Establish inspection, maintenance and monitoring strategy based on RUL obtained, uncertainties and a risk assessment procedure as described in Clause 6.

10.2.2 Absolute assessment

An absolute assessment aims to determine the absolute damage of a component from which its RUL is then estimated. In contrast to the relative assessment, the adopted damage model needs to be more sophisticated and hence more data and information on the turbine/component under consideration are needed. Since absolute values are used instead of relative ones, this approach is more sensitive to model inaccuracies (or - in the case of load measurements - to measurement inaccuracies) and should only be performed when accurate knowledge is available of the physical and geometrical properties of the turbine/component, as well as of the turbine control and safety system.

More guidance on data requirements for this approach can be found in Annex B.

The assessment may either be deterministic, semi-probabilistic or probabilistic. Deterministic methods shall be verified and comply with appropriate design standards, for example, IEC 61400-1 [N.1]).

Instead of deriving loads from aero-elastic simulations, they may alternatively be obtained from suitable measurement-based methods, see Clause 10.2.2.3.

Depending on the component, the assessment shall be in accordance with applicable state-of-the-art standards and guidelines.

10.2.2.1 Deterministic assessment

The deterministic approach should adhere to the following steps:

- Use aeroelastic model and component models that are sufficiently validated e.g., with load measurements
- Calculate absolute RUL using site-specific wind conditions
- Adequately estimate RUL uncertainties
- Establish inspection, maintenance and monitoring strategy based on obtained RUL, its uncertainties, and a risk assessment procedure as per Clause 6.

10.2.2.2 Probabilistic assessment

In a probabilistic assessment, the reliability (or, in other words, the probability of failure) of a component is quantified and compared to a desired target minimum level. From this comparison a RUL estimate can be derived. For more information on the probabilistic approach the reader may refer to the EN 1990 [N.37], ISO 2394 [N.28] or JCSS Model Code [I.13].

In a probabilistic approach, the following should be undertaken:

- Use aeroelastic model and component models that are sufficiently validated e.g., with load measurements
- Calculate probability of failure/reliability using site-specific wind conditions
- Establish inspection, maintenance and monitoring strategy based on obtained probability of failure/reliability and a risk assessment procedure as described in Clause 6

10.2.2.3 Measurement-driven assessment

Structural components of the primary load path (for example, blades, tower, foundation, etc.) can be monitored with adequate and validated direct or indirect, short- or long-term load measurement campaigns.

It is strongly recommended to only use systems that are validated, as, for example, by a load monitoring campaign according to IEC 61400-13 [N.7]. For more general guidance on structural health monitoring and requirements, the reader may refer to [N.4] and Clause 8.3 of this TS.

Based on these data either the deterministic or probabilistic approach may be followed to determine the RUL of the respective component.

10.3 Model data, input data and their uncertainties

A detailed list of information and data should be prepared in order that lifetime assessment can be carried out for each failure mode of each component in the primary load path.

Minimum requirements needed to perform an analytical assessment of RUL are given in Annex B, which also makes recommendations about data suitable for the different approaches outlined in Clause 10.2.

Uncertainties in the whole process shall be evaluated. This must be done per component and failure mode since the sensitivity for uncertainties will differ for each component and the turbine safety will be compromised by the weakest of the components in the primary load path and critical safety systems. The evaluation of the uncertainties might show the need to reconsider and extend the chosen approach.

The more data of good quality, the lower the uncertainties on the predicted RUL. Any consistent RUL estimation process needs to take proper account of uncertainties (as described in this Clause) and needs to penalize higher uncertainties with lower RUL.

Uncertainty evaluations need to be carried out for the following elements of the analysis, at least:

- Environmental data (such as atmospheric turbulence, wind speed distribution, wave parameters)
- Aeroelastic model (such as models and parameters intended to represent aerodynamic and structural behaviour, control system)
- Measurements (if applicable)
- Fatigue damage model (for example, the application of simplified damage equivalent loads, S-N curve parameters, theories of crack initiation, growth, and possible application of fracture mechanics)

The uncertainties for environmental parameters depend on the accuracy with which they are estimated (examples include long-term on-site measurements combined with extreme-value statistical approximations, numerical models, operational turbine data).

The uncertainties relating to the accuracy of the model should be quantified for each relevant mode of failure and the ability of the model to predict the remaining life with respect to that mode of failure should also be quantified. Model uncertainty assessment encompasses all parameters of all models used to model the turbine design and determine the lifetime. The assessment of model uncertainty shall take account of uncertainties regarding aerodynamic, hydrodynamic, structural, material behaviour, the operational behaviour, and all other important physical characteristics. The following questions may help assess uncertainties:

- Has verification of the numerical model (software) demonstrated sufficient convergence with observed behaviour of a similar turbine?
- How well do model parameters correspond to the as-built state of the turbine?
- Does the model reproduce load relevant operational behaviour to a sufficient degree?
- How well are the design assumptions known and validated?
- How well does the model fit into general knowledge about wind turbine design or field experience?
- How important are the single parameters for the component and failure mode in focus?

The model uncertainties are thus determined as a combination of the features of the model, its validation, agreement with measurements, agreement with inspection reports and known failures.

In case that load measurements are used in the assessment, their uncertainties shall be considered.

The fatigue damage model shall be suitable and representative for the component and account shall be taken of related uncertainties. The various approaches to the assessment (see Clause 10.2) may require fatigue damage models of different complexity. For complex components, for example, blades, or components with complex internal structural or material properties, for example gearbox or jacket structures, the loads derived from the aero-elastic model may not be directly representative for fatigue damage and hence suitable sub-structuring models may have to be applied if the RUL of such components is to be estimated. All assessments shall be in compliance with state-of-the-art design approaches. It should be noted that state-of-the-art fatigue damage models may differ from those used in the original turbine design. It shall be demonstrated that the RUL estimated is conservative. Evidence shall also be provided about the associated uncertainties.

Relevant failure modes for structural or major components shall be defined in accordance with IEC 61400-1, for example, fatigue crack initiation of fibre or matrix in the spar caps of the blade structure.

The uncertainty evaluation of RUL shall account for both the magnitude of uncertainties of the considered parameters (as enumerated above) as well as for the sensitivity of RUL with respect to these parameters.

In case of serial connection of multiple models (commonly load and stress calculations), the model uncertainty per failure mode and component may be determined as the product of the uncertainties of the single models.

For each component and failure mode thus investigated, a RUL value and uncertainty/tolerance must be given. It must be understood that the RUL gives the remaining operational lifetime after which the structural reliability of the primary load path component under consideration drops below its design requirements.

Annex A: Health and safety – inspection and performance criteria [INFORMATIVE ANNEX]

The scope of IEC TS 61400-28 primarily sets out requirements and guidance based on IEC documents including IEC 61400-1 [N.1] and IEC 61400-3 [N.3] series. Health and safety requirements are therefore narrowly defined in these standards and are primarily restricted to consideration of the topics in the following list:

- Confirmation of structural integrity of components within the primary load path
- Continuity and correction function of lightning protection system (where installed)
- Verification that control and safety systems are safe and continue to function, ensuring structural loads remain within safe limits throughout the design life and do not:
  - exceed elastic limits,
  - compromise the primary structure
- Confirmation the WTG remains safe to enable access and egress of personnel, during visits to undertake maintenance, inspection, or other similar tasks

However, it may be found very useful to scrutinise evidence that robust systems have been set up, followed, reviewed, revised and consistently documented throughout the operational life of the wind farm, in compliance with all governing local HSE regulations.

In most cases, national regulations do not require duty holders (for example, current asset owner) to retrospectively upgrade plant, equipment or control systems to meet any more recent regulatory standards or state of the art as defined by, for example, updated technical standards (for example, IEC).

However, it is accepted good practice and, in some cases, a legal duty to ensure suitable and sufficient risk assessments are carried out and reviewed on a regular basis. These reviews could potentially identify that risks have not been reduced to as low as reasonably practicable (ALARP). The risk assessment may also identify good practice opportunities to improve or upgrade installed equipment or safety controls, noting these may also have operational and performance benefits as well.

The scope of potential inspections/checks to be performed are described below. National regulations may define statutory inspection requirements (for example, lifting equipment, fall arrest systems) or other health and safety duties. This informative annex sets out an indicative list of checks, evidence and processes that may be deemed appropriate to conduct to validate health and safety risks for the WTG. The detail and depth of these checks will primarily be driven by the risk tolerance of the parties involved and as necessary any contractual, financial or regulatory requirements that may be mandated in order to permit the life extension to be sanctioned.

The examples set out below are mainly to assist in defining the scope of end-of-life assessments. However, the scope also provides relevant check that could be expected to be carried out during the operation and maintenance phase.

Examples would include, but may not be limited to:

Processes

- Evidence of formal health and safety risk assessments specifically addressing end of life risks
- Review of current regulations and standards to determine the scope and practicality of making any improvements or upgrades

- A check on any relevant safety alerts or product recalls as applied to the turbine, subsystems or components
- A check on any failure to the turbine or subsystems received or any failures of safety critical systems
- Access to health and safety manuals, technical files for turbine and key subsystems including drawings and schematics if available

Inspection Evidence

- Statutory or equivalent inspection certification covering:
  - lifting equipment (for example, hoists)
  - access lifts
  - anchor points
  - climbing aids
  - fall arrest systems/devices
  - pressure and hydraulic systems
- Evacuation equipment (if installed as a permanent asset)
- Ladders
- Hatches
- Control and protection systems
- Guard rails and collective protection systems
- Alarms (for example, fire), if installed
- Fire suppression, if installed
- Fixed electrical systems
- Static grounding systems

Visual Condition of the Turbine

- Signs of leaks
- Condition and visibility of safety signage
- Emergency evacuation notices
- Signs of mould or other organic growth
- Evidence of wildlife damage or infestation (for example, guano)
- Lighting/emergency lighting
- Aviation lighting
- Cable management

- General housekeeping
- Condition of surface treatments (for example, paint)

Note that this technical specification only considers the WTG. However effective health & safety processes and due diligence checks in many cases will also need to consider interfaces and risks with associated balance of plant (for example, switchgear, substations etc.) and other site infrastructure.

A.1 Content and format of any reports issued

In presenting the findings of any inspections or audits conducted on the assets, suitable report formats should normally be adopted. Some jurisdictions may specify the scope and content of inspections to be carried out, but examples of what information could be detailed in a report include, but may not be limited to:

- Name and address of the person(s)/company for whom the report was commissioned
- Site and asset details to which the report applied
- Dates when the inspection(s) were carried out
- Details and known particulars of the assets(s)/WTG's
    - date of manufacture
    - details and date of any modifications
- Date(s) of the last thorough examination
- Safety performance criteria/limits of the asset/system inspected (for example, safe working loads)
- Details of examinations performed (for example, visual/physical test)
- Results of the inspection and how judged
    - design performance
    - written scheme of examinations
    - statutory performance limits
- Statements and conclusion as to the status and safety of the assets inspected
- Identification and details of any defects that are, or could become, a danger to persons including
    - a description of the defect(s) including their severity to persons at risk
    - particulars of any repair, renewal or alteration to remedy the defect(s)
    - estimated costs for correcting the fault
    - timelines to rectify the faults found to be a danger to persons
- Name and address of a person signing or authenticating the report
- Date of the report

A.2 Operation and maintenance data

Operational data about the primary load path that may be collected and reviewed through life and/or at the end of design life include:

- Serial make and model
- Original design documentation and ‘as built’ drawings
- Commissioning records including any test results
- First maintenance after commissioning and any test results
- Maintenance procedures
- Maintenance records including:
  - dates and records of planned maintenance; any missed or significantly delayed maintenance task[s]
  - dates and types of fault events, fault category, failure modes and intervention activity undertaken
  - major components exchanged
  - minor components (of significance) exchanged
  - periods of significant down-time through curtailment; ice control; shadow control
  - function and safety tests
  - numbers and timing of starts, stops, emergency stops and grid outages
- Blade Inspection records and reports (internal; external)
- Blade repairs or replacements (on site; on delivery; at the factory)
- Significant downtime events
- SCADA data
- Condition monitoring data
- Test results and frequency including, for example, oil and grease analysis
- Non-conformities
- Health and safety information
- Inspection reports and records
- Any significant changes to software or software parameters and the effect on the operation of the wind turbine (for example, operating temperatures, power output, noise parameter settings) that may affect Useful Life of a Safety Critical Component.
- Change log:
  - structural changes to the wind turbine
  - wind farm array changes including extension, repowering and removal of wind turbines that might affect turbulence intensity
- Meteorological data from site met mast or wind turbine anemometer

Operational data about the high voltage electrical system that may be collected and reviewed through life and/or at the end of design life include:

- Maintenance records for internal transformer or switchgear both visual and intrusive.
- Maintenance manual and instructions, ideally from the OEM where available
- Test results and frequency including oils and gas content

- Transformer and switchgear repairs or replacements (on site; on delivery; at the factory)

Annex B: Data requirements for primary load path [INFORMATIVE ANNEX]

B.1 Input data requirements

The tables below describe the information and data requirements for the following approaches to remaining life assessment:

- Inspection only: as described in Clause 7
- Relative assessment, as described in Clause 10.2.1
- Absolute assessment:
  - Deterministic assessment as described in Clause 10.2.2.1
  - Probabilistic assessment as described in Clause 10.2.2.2
  - Measurement-driven assessment as described in Clause 10.2.2.3

In cases where the subject of the required documentation is not clear, it shall be assumed that requirements are for components in the primary load path.

Classification has been carried out using the descriptors Blank = not required, R = recommended, M = mandatory. Where the requirement is mandatory (M), this specifies the minimum information or data that must be available in order to proceed with the assessment. If minimum requirements are not met for any reason, then specific activities should be undertaken to acquire the information or data, or any assumptions justified and subjected to uncertainty analysis.

Where the requirement is recommended (R), this indicates that the information or data contributes increasingly towards lessening uncertainty in the overall outcomes.

Table B.1

	Inspection only	**Relative Assessment**	**Absolute Assessment**		
			Deterministic	**Probabilistic**	**Measurement-driven**
Wind Turbine Technical Information					
Manufacturer and type		R	R	R	R
Wind class		M	R	R	R
Design life		M	R	R	R
Site Data					
Wind farm layout		R	R	R	R
Metmast positions and configuration		R	R	R	R
Neighbouring wind turbine locations		R	R	R	R
Neighbouring wind turbine commissioning		R	R	R	R

Table B.2

	Inspection only	Relative Assessment	Absolute Assessment		
			Deterministic	Probabilistic	Measurement-driven
Design Documentation					
Design codes and methods		M	R	R	R
Design calculations		R	R	R	R
Schematic arrangement drawings	R	R	R	R	R
Design drawings		R	R	R	R
Design power histogram		R	R	R	R
Power curve		R	R	R	R
Thrust coefficient curve		R	R	R	R
Rotor speed vs wind speed		R	R	R	R
Pitch angle vs wind speed		R	R	R	R
System and component specifications	R	R	M	M	M
Site suitability assessment by developer or OEM	R	R	R	R	R
Design FMEA	R	R	R	R	R

Table B.3

	Inspection only	Relative Assessment	Absolute Assessment		
			Deterministic	Probabilistic Assessment	Measurement-driven
Detailed Design Documentation					
Blade characteristics (aerodynamic, structural and geometry)		R	R	R	R
Blade frequencies flap/edge		R	R	R	R
Blade damping		R	R	R	R
Hub structural and geometry characteristics		R	R	R	R
Nacelle structural and geometry characteristics		R	R	R	R
Drive train stiffness, damping and frequencies		R	R	R	R
Tower structural and geometry characteristics		R	R	R	R
Tower frequencies		R	R	R	R
Foundation structural and geometry characteristics		R	R	R	R
Design evaluation reports (third party)		R	R	R	R
Probabilistic analysis report				R	
Control system description (PI parameters etc)		R	R	R	R

1896 **Table B.4**

	Inspection only	Relative Assessment	Absolute Assessment		
			Deterministic	Probabilistic	Measurement-driven
Climate Data					
Turbulence intensity distribution		M	M	M	R
Temperature		R	R	R	R
Air Density		R	R	R	R
Wind Direction Distribution		M	M	M	R
Wind Speed Distribution		M	M	M	R
Average vertical shear (wind shear)		M	M	M	R
Up flow (inflow)		M	M	M	R
Degree of icing		R	R	R	R
Special events (negative wind shear, gust events…)		R	R	R	R
Wave and Sea State parameters (for offshore)		M	M	M	R

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Table B.5

	Inspection only	Relative Assessment	Absolute Assessment		
			Deterministic	Probabilistic	Measurement-driven
Operational History					
Commissioning report	R				
Operation manual	M	M	M	M	M
Actual power histogram		R	R	R	
Running, stopped and downtime hours		r	R	R	R
Actual number of start/stops including emergency		R	R	R	R
Wind data from nacelle anemometer (SCADA)		R	R	R	R
Main operational variables from SCADA (power, rpm, pitch, yaw)		R	R	R	R
End of warranty inspection	R				
Yaw misalignment		R	R	R	R
Event/Fault code record in SCADA	R	R	R	R	R
Fault/event code list (load related fault/event is important)	R	R	R	R	R
Environmental requirement (eg noise, shadow)		R	R	R	R

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Table B.6

	Inspection only	Relative Assessment	Absolute Assessment		
			Deterministic	Probabilistic	Measurement-driven
Maintenance and Field History					
Maintenance manual (lubrication schedule)	M				
Spares consumed	M	M	M	M	M
Software upgrades (upgrade time, program version, parameter configuration version)		R	R	R	R
Modification history and retrofit	M	M	M	M	M
Failure analyses	R	R	R	R	R
Hardware upgrades (upgrade time, spares type change, new functional device)	M	R	R	R	R
On-site work orders	R				
Fault troubleshooting reports	R				
Repairs (eg weld repairs)	M	R	R	R	R
Repair procedures	M				
Inspection History					
Inspection manual	M				
Inspection Reports (NDE etc)	M	R	R	R	R

Table B.7

	Inspection only	Relative Assessment	Absolute Assessment		
			Deterministic	Probabilistic	Measurement-driven
Measurements					
Condition monitoring measurements (eg vibration)	R	R	R	R	R
Load measurements (eg blade, main shaft, tower)		R	R	R	M
Wind speed measurements		R	R	R	R
Turbulence intensity measurements		R	R	R	R
Ambient temperature		R	R	R	R
Pitch electric motor-current or hydraulic ram pressure	R				
Main shaft bearing temperature	M				
Yaw misalignment		R	R	R	R
Hydraulic system oil temperature	R				
Bolt tension measurement	R				
Foundation crack tip opening gauges, seismometer, low frequency accelerometer, inclinometer	R				

Table B.8

	Inspection only	**Relative Assessment**	**Absolute Assessment**		
			Deterministic	**Probabilistic**	**Measurement-driven**
Condition Monitoring					
Rotor system - grease sampling of pitch bearings (wear metals, water content)	R				
Main bearing - grease sampling (wear metals, water content)	R				
Lubrication system - oil sampling (wear metals, water content)	R				
Hydraulic system - oil sampling (wear metals, water content)	R				
Materials Data					
Material type and specification		R	M	M	M
Material fatigue curve		M	M	M	M

B.2 Condition monitoring data requirements

The following is a non-exhaustive list of parameters that can be monitored for condition monitoring and structural health monitoring in a more specific and complementary to Clause 4 *Data requirements* from ISO 13381-1 [N.34]. The owner/operator should adapt it to their needs/risks assessment according to the specific turbine design. Some may not be directly connected to structural safety, but the combination of parameters monitoring is the way to detect early deviations that would lead to structural failures if not corrected/mitigated.

With regards the origin of the data to be used, online sources and processing shall be favoured over offline strategies.

1916 **Table B.9**

WTG component or device	Evaluation	Data origin	Benefits	Primary (P) /secondary (S) load path
Rotor mass and aerodynamic imbalance	Good to have	Offline, in one shot at commissioning and after blade or pitch bearing exchange. Online, measurement and model based. Also after the limit switch setting or exchange	Avoid additional loads due to static and dynamic imbalance	P
Pitch motor 1s or RMS current	Recommended	From SCADA data	Pitch bearing possible monitoring	P
Pitch cylinder pressure and position measurement for each cylinder	Recommended	From SCADA data	Pitch bearing possible monitoring	P
Pitch cylinder proportional valve opening	Recommended	From SCADA data	Supports diagnosis of pitch system health	P
Pitch speed	Recommended	From SCADA data or control system (if available)	Deviation between demanded and actual	P
Blade cracks monitoring system	Recommended	-	-	P

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1919 **Table B.9 (cont'd)**

Blade load measurements. Warning: such systems are giving deflections. Load calibration is almost impossible as deflections are non-linear under combined loads	Good to have	Measurement and model based. More direct measurements such as blade loads sensors can be used	Structural integrity monitoring and necessary information for blade fatigue load calculation	P
Lightning strike counter/measurement	Recommended		If possible, intensity and dI/dt measurement will allow to distinguish if effective lightnings are inside the range of the LPS	P
Off-line grease condition monitoring for pitch bearings	Highly recommended		Only way to ensure that lubricant is clean enough. Unique way for now to monitor early wear	P

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1921 **Table B.10**

Main Bearing				
Temperature measurement	Highly recommended	From SCADA data (1h or 24h average)	Analysis of incoming data compared to historically “good” values in the same operating conditions may allow to detect early deviations even at partial loads. Increasing temperature is sign of latest stage Fault	P
Off-line grease particle counting and condition monitoring	Highly recommended		Ensures that lubricant is clean enough. Very efficient early wear detection	P
Load measurement	Good to have for at least three representative turbines per site		Could allow a review of the design loads regarding real loads at final commissioning or at the end-of-warranty to challenge the site load assessment, typically by the developer or OEM at procurement level	P
Vibration Monitoring System	Highly recommended		Very early detection of spalling with shock detection (for example)	P

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1923 **Table B.11**

Gearbox				
Vibration Monitoring System	Highly recommended		Allows very early detections of spalling on bearing and gears and defect location	S/P
Temperature measurement and monitoring of oil sump, after cooling, of bearings when possible	Highly recommended	From SCADA data	Deviations in temperature would lead to poor lubrication conditions and early fault of mechanical parts. Analyzing and solving temperature deviations early will preserve the components. Bearing temperature will raise at final fault stage allowing decision for exchange. Analysis of incoming data compared to historically “good” values in the same operating conditions may allow to detect early deviations even at partial loads	S/P
Off-line oil particle counting and oil condition monitoring	Highly recommended		Ensures that lubricant is clean enough. Very efficient and cheap early wear detection. Complementary to VMS to quantify fault rate and to avoid secondary failures	S/P
On-line oil condition monitoring	Good to have		Allows monitoring of lubricant quality. May not be yet accurate enough to go for condition-based oil exchange	S/P
On-line measurement of oil cleanliness level	Good to have		May measure lubricant cleanliness but may not allow to distinguish hard particles neither particles material	S/P
On-line metal particle counting	Recommended		In addition to vibration monitoring, allows very early detections of spalling on bearings and gears	S/P

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Table B.12

Yaw mechanism				
Current and temperature of each gearmotor	Recommended	From SCADA data	Analysis of incoming data compared to historically "good" values in the same operating conditions may allow to detect early deviations even at partial loads showing gear motor bad cooling, brake malfunction, gearmotor over torque, yaw gear wear, yaw bearing wear	P
For yaw systems comprising rolling element bearings, off-line bearing grease particle counting and grease condition monitoring	Highly recommended		Ensures that lubricant is clean enough. Very efficient and cheap early wear detection	P
Monitoring of nacelle/yaw bearing and yaw bearing/tower flange bolt or stud clamping force	Recommended		Reduces fatigue on bolted structural connections, avoids retorqueing when tension is OK, when ageing ensures the clamping force when torqueing may be jammed by rust or friction between nut and screw. Reduced torsional fatigue on the screw. Reduces maintenance time with faster check of tension without torqueing machine	P

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Table B13

Tower				
Tower flange bolt clamping force monitoring	Good to have		Reduces the fatigue on bolted structural connections, avoids retorqueing when tension is OK, when ageing ensures the clamping force when torqueing may be jammed by rust or friction between nut and screw. Reduced torsional fatigue on the screw. Reduces maintenance time with faster check of tension without torqueing machine	P
Tower resonance	Highly recommended	From SCADA data		P
Tower vibration and or strain sensors	Good to have			P

Table B.14

Foundation				
Load on foundation	Recommended	Separate monitoring system or included in original supply of turbine	Determines loads on foundation due to sea and wind state	P
Concrete sampling	For certification, might be Highly recommended for lifetime extension	Sampling and destructive testing or inspection	Determines condition of foundation for use or continued use	P
Inclination of foundation	Recommended	Separate system or included in original supply of turbine	Determines permanent deformation (eg displacements of the structure in the soil)	P

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Site condition measurements				
Horizontal wind speed measurement	Highly recommended	From the nacelle anemometer behind the rotor plane with high uncertainties or from third party anemometers in the (spinner anemometer) or in front of the rotor plane (remote sensing)	Average wind speed measurement is a necessary information for fatigue load calculations	P
Rotor equivalent wind speed measurement (REWS)	Good to have	Nacelle Lidar at least on three representative turbines (wind directions and inside the WF) for at least one-year period	Will allow to connect load with the wind conditions at the rotor plan.	P
Inflow angle and Yaw Misalignment	Recommended	Suitable third-party anemometers in (spinner anemometer) or in front of the rotor plane (remote sensing).	Inflow angles and uncorrected yaw misalignment increase the loads to the wind turbines during operation	P
Wind shear up to the tip height	Good to have	Lidar at least on three representative turbines (wind directions and inside the WF) for at least one-year period	Will allow to connect load with the wind conditions at the rotor plan.	P
Turbulence Intensity	Recommended	From the nacelle anemometer behind the rotor plane with high uncertainties or from suitable third-party anemometers in the (spinner anemometer) or in front of the rotor plane (remote sensing)	Turbulence intensity is necessary information for fatigue load calculations. It might change over the operational life due to growing (forests) or built obstacles (other turbines, industrial development).	P
Wave heights and directions (offshore)	Recommended	For example, from wave radar placed outside the tower and facing down to the water surface. Typically mounted in the railing or girder of the outer platform and the tower entry level	Sufficient to characterise the oceanographic conditions at the site for loading of the structure	P

Annex C: Physical inspections - best practice for documentation of results, findings and insights [INFORMATIVE ANNEX]

C.1 Physical Inspections

The inspection checklist that can be used as a guide for each of the inspection regimes outlined in the Technical Specification is shown below. It assumes there are no pre-eminent faults identified in these areas. The inspection frequencies recommended by the OEM shall be observed as a minimum, unless variations from these can be justified by more advanced analysis, demonstrating equipment reliability levels. The minimum period of time between inspections shall be the default.

Tables C.1 to C.

This checklist can be used in conjunction with the text later in this Annex which describes the typical inspection techniques for each of the inspection tasks.

O – Optional

R – Recommended

HR – Highly Recommended

Table C.1

Inspection task	Early life/end of warranty	Mid life inspections	Life extension inspections
Normative			
Tower			
Visual Inspection of Structural Welds	O	R	HR
NDT examination of Structural Welds	O	R	HR
Corrosion Level	O	R	HR
Check Verticality	R	R	HR
Deflection check (if embedded can foundation)	R	R	HR
Blades			
Visual inspection of aerofoil surfaces	R	R	HR
Inspection of blade root areas	R	R	HR
Visual inspection of blade internal areas	R	R	HR
Pitch system			
Visual inspection of the high stress areas of the blade bearing	R	R	HR
NDT inspection (see notes in body text)	R	R	HR
Grease analysis	R	R	HR
Emergency function test	R	R	HR
Yaw ring and bearing			
Visual inspection of teeth	R	R	HR
Visual inspection of bearing	R	R	HR
Grease Analysis	O	R	HR
Foundation			
Visual inspection of grout	R	R	HR
Inspection of holt down bolts	R	R	HR
Visual inspection of any visible elements of the foundation	R	R	HR
Embedded can inspection to check for water ingress/concrete grinding damage	O	R	HR
Transition piece			
Visual Inspection of all visible areas	R	R	HR
NDT of significant welded joints	O	R	HR
Check cable seal condition	R	R	HR
Measure rate of corrosion	O	R	HR
Nacelle frame/bedplate			
Visual Inspection of all visible areas	R	R	HR
Visual inspection of structural welds	R	R	HR
NDT of structural welds (based on results of above inspection)	O	R	HR

Table C.2

Inspection task	**Early life/end of warranty**	**Mid life inspections**	**Life extension inspections**
Hub			
Visual Inspection of all visible areas of hub structure	R	R	HR
NDT to check situation of pre-existing casting defects	O	R	HR
Visual check of integrity of mounted ancillary components	R	R	HR
Bolted connections			
Removal of sample of bolts to inspect for corrosion	R	R	HR
Visual check for position changes (through markings applied to bolt head and mating surface)	R	R	HR
Tap test	O	R	HR
Safety system			
Functional check of all elements of the turbine safety system	R	R	HR
Main Bearing			
Visual inspection of main bearing	R	R	HR
Check integrity of seals	R	R	HR
Analysis of grease	O	R	HR
Visual inspection of main bearing housing	R	R	HR
NDT of housing	O	R	HR
Main Shaft			
Visual check of shaft	R	R	HR
NDT check of original forging defects	O	R	R

Table C.3

Inspection task	Early life/end of warranty	Mid life inspections	Life extension inspections
Informative Elements			
Gearbox			
Boroscope Inspection	R	R	R
Swarf magnet check	R	R	R
Oil Analysis	R	R	R
Generator			
Inspection of bolted joints/mounting points	R	R	R
Alignment of generator to gearbox	R	R	R
Visual inspection of grease - analyse if discoloured	O	R	R
Generator			
Inspection of bolted joints/mounting points	R	R	R
Alignment of generator to gearbox	R	R	R
Visual inspection of grease - analyse if discoloured	O	R	R
Air gap check - inspection for ingress of dirt and foreign objects	R	R	R
Inspect slip ring and brush	R	R	R
Visual inspection of associated cabinetry	R	R	R
Yaw Drives			
Visual check of pinion and gearbox where feasible	R	R	R
Functional check	R	R	R
Nacelle Condition			
Visual inspection to include (as a minimum) GRP structure, attachment points, hatches, fixings	R	R	R

C.2 Inspection scope

The inspection approaches that could be used to satisfy the requirements of the table set out above are described in the following Clauses.

C.3 Highly recommended inspections

C.3.1 Tower

The purpose of the inspections should be to determine whether any defects are present in the structural elements. This should include at least the following points:

- Visual inspection of structural welds (these will need to be identified from the original fabrication drawings or by carrying out a 100% visual inspection of the structure)

- This can be supplemented by the use of non-destructive examination techniques if surface breaking defects are present to determine crack length and depth
- Recording the extent of any corrosion present and whether there is a measurable loss of corrosion protection
- Check the verticality of tower and compare to commissioning records (if conducted).

The inspection report should indicate the severity of each of the findings and the potential impact on extended operation (LTE). It should include at least the following points:

- The inspection/testing scope (visual and/or NDT)
- Findings recorded on a drawing (preferred) or table (accepted)
- NDT findings should include information on defect position, length and maximum depth
- Comparison with previous inspection reports is considered advantageous, so the rate of progression of findings can be assessed.

C.3.2 Blades

The blade inspections should focus on the determination of the structural integrity of the blade. This can be achieved by the following points:

- Visual inspection by an appropriate means to check aerofoil surfaces, leading edge (LE) or trailing edge (TE) for excessive wear/damage/cracking/failure
- Visual inspection and NDT (where feasible) of the blade root areas
- Visual inspection of the interior of the blade to detect any failure of the laminate or the main spar(s). It should be noted if interior inspection of the blade is not feasible, then the uncertainty level of the blade life extension will be high and may require more frequent external inspections.

The inspection reports should include the following points:

- The inspection/testing scope (visual and/or NDT).
- Findings recorded on a drawing (preferred) or table (accepted).
- Photographs of findings.
- Blade erosion should be recorded in terms of its location on the blade (spanwise and chordwise, suction side or pressure side) and also its extent spanwise and chordwise. Depth of erosion should be recorded,
- Comparison with previous inspection reports is considered advantageous, so the rate of progression of findings can be assessed.

C.3.3 Pitch bearings

Visual inspection and NDT by an appropriate means in high stress areas (if it is not possible to determine where these are, it may necessitate a full inspection of all areas including in the bore holes of the pitch bearing structural fasteners). It is most important that NDT inspection is carried out on turbines where the blade is attached to the outer race of the pitch bearing.

Grease shall be analysed to determine whether there are numbers and sizes of iron or chromium particles that indicate wear or damage beyond acceptable levels. Annex E.6 provides further guidance. If limits are exceeded, further inspection or replacement of the pitch bearing is recommended.

The inspection reports should include the following information:

- The inspection scope (visual and/or NDT)
- The bearing type (for example, double roller bearing), manufacturer and the serial number plus any descriptive information (such as any corrosion protective coating applied, and to which surfaces)
- A drawing of the bearing with any defects recorded in a representative manner in the corresponding location
- The NDT procedure used (if applicable) to include all preparation requirements, consumables, technique and results
- Grease analysis results (where applicable)
- Photographs of finding.

C.3.4 Yaw ring and bearing

Visual inspection of the yaw ring to check for condition of the teeth and general integrity of the area in terms of excessive wear and cracks. Also check that there is no excessive leakage of grease from the yaw bearing and no other issues detected.

The inspection reports should include the following information.

- Inspection scope
- Yaw ring description and information (general arrangement drawing, material)
- Photographs of defects (preferably with reference measurements such as length, depth, area)
- Grease analysis results (if undertaken)
- The NDT procedure used (if applicable) to include all preparation requirements, consumables, technique and results.

C.3.5 Foundation

Visual inspection of the foundation, by means of at least the following points:

- Visual inspection of the grout for cracking and loss of integrity permitting water ingress. Inspect structural fasteners for integrity and corrosion
- Further inspections can include taking core samples if this is appropriate and also measuring the tower deflection
- In case of embedded steel part (cast-in can), check the water tightness between concrete and steel, check for concrete grinding signs inside the foundation and, if necessary, assess impact of any water ingress.

The inspection reports should contain the following information:

- Inspection scope
- Foundation description and information (general arrangement drawing, material)
- Photographs of defects (preferably with reference measurements such as length, depth, area
- Core sampling results (if undertaken)
- Tower deflection measurement procedure and results.

C.3.6 Transition piece (Offshore)

The focus of the inspections of the transition piece should be the level of integrity and the rate of corrosion. There will be a level of corrosion protection considered in the design (in terms of materials used) and the maintenance (application and re-application of corrosion protective coatings, seals, water ingress etc.). Throughout the life of the asset, it is recommended that the integrity (for example, the extent of cracking of welded joints) and the rate of corrosion are monitored since this can have significant, negative, impact on fatigue life.

A suitable inspection regime should therefore contain the following points.

- Visual inspection to assess general condition
- NDT of any significant welded joints
- With the transition piece, monitoring rate of corrosion using coupons may supplement inspections to allow for a level of quantitative monitoring of rates
- Monitoring condition of the seals around the cable entries throughout the life of the asset would be prudent. If the foundation /substructure corrosion protection design relies on the exclusion of oxygen from internal volumes, then seal failure can result in accelerated corrosion

The inspection reports should include the following information.

- Inspection scope
- Drawing of the transition piece (fabrication drawings, if available, otherwise a general arrangement with key welds highlighted)
- NDT procedure and findings
- Results of any corrosion monitoring
- Photographs of findings.

C.3.7 Nacelle frame/bedplate

The nacelle bed plate design should be reviewed to confirm locations of structural welds. Any design information which the owner/operator may have will be particularly useful in this regard. Where components having significant mass are located at the extremes of the nacelle bedplate (it is commonplace for transformers to be located at the rear of the nacelle in some design philosophies), thorough inspection of the structure underneath here should be given focus to check for cracking.

A suitable inspection regime should include carrying out the following activities:

- A thorough visual inspection of the structure to assess for integrity, with a focus on the mounting areas of any major components
- NDT of structural welds where surface breaking defects are visible to assess for length, depth and position

The inspection reports should include the following information.

- Inspection scope
- Drawing of the nacelle frame/bedplate (fabrication drawings, if available, otherwise a general arrangement with key welds highlighted)
- NDT procedure and findings
- Photographs of findings.

C.3.8 Hub

The hub and associated components should be visually inspected for integrity. The original casting certificates and associated NDT records will prove valuable if these have been received. Monitoring any casting defects throughout the life of the WTG will be helpful to determine whether defect growth is occurring and assist in the formation of a strategy to manage the condition moving forward.

A suitable inspection regime should include carrying out the following activities:

- Visual inspection of all areas of the hub casting – reference to known defects would be helpful
- NDT of original casting defects where feasible (these may be sub surface)
- Visual check of the ancillary component mountings and mounting locations

The inspection reports should include the following information.

- Inspection scope
- Drawing of the hub (fabrication drawings if available otherwise a general arrangement)
- Original NDT of hub casting with defects if available
- NDT procedure and findings
- Photographs of findings.

C.3.9 Bolted connections

Monitoring the integrity of the bolted connections should be a through-life activity and commissioning and installation records are of primary importance here to ensure the original lubrication and installation procedures were correctly followed. Through-life sample torque checks are typically included as part of the OEM maintenance instructions and position marks may have been made on the fastener and mating surface. The key to ensuring that the integrity of bolted joints is maintained is to ensure that the fasteners are tensioned to the correct value. Techniques that involve direct measurement of tension will give much lower uncertainty than torque-based measurements, as the relationship between torque and tension is very sensitive to variation in thread friction.

A suitable inspection regime should include carrying out the following activities:

- A sample of fasteners should be removed and inspected for corrosion, as this could alter the surface finish of smooth machined shanks and reduce their fatigue lives. As fasteners are tensioned close to yield, there is little benefit in testing for cracks, as the interval from a detectable crack being present, to failure occurring, is likely to be very short
- Inspecting any historical markings for positional changes

The Inspection reports should include the following information:

- Inspection scope
- Description of fasteners used and any specification changes made during the operational life of the site
- Review of maintenance actions/strategy undertaken (bolt torque checks, preload measurement, tension measurement)
- Any RCA carried out on failed bolts
- NDT procedure and findings if utilised
- Photographs of findings

C.3.10 Safety systems

All components of safety and protective systems should be inspected for condition and functional performance (refer to IEC 61511 series, chapter 16 *Operation and Maintenance of Safety Instrumented Systems* [N.31] [N.32]).

This could include:

- Inspection and testing (where possible) of the pitch system, especially the emergency pitching system
- Testing the overspeed system including the sensor. Injection testing is typically used here to test the system response but often does not include testing of the sensor and this is a vital part of that system

The inspection reports should include the following information:

- Inspection scope
- Description of the Safety System
- Description of the test procedure
- Results of the testing
- Photographs of findings

C.3.11 Main bearing

Inspection of the main bearing is described below:

- A visual inspection of the main bearing (where feasible) including the pedestal housing. One of the main concerns with the main bearing housing is cracking around the transition from the nacelle bedplate mounting points to the vertical bearing housing
- Inspections of the main bearing sealing to check for integrity and movement.

The inspection reports should include the following information:

- Inspection scope
- Results of the inspection
- Photographs of findings.

C.3.12 Main shaft

The main shaft should be checked for integrity. This should include a method for detecting cracking, observing and recording damage arising from fretting, spalling and scoring, particularly in the region between the hub and main bearing.

Reviewing the original forging certificates, if supplied may identify sub-surface defects and periodic NDT of the shaft may prove useful to monitor whether these defects have changed during the life of the Turbine.

The inspection reports should include the following information:

- Inspection scope
- Any NDT inspection reports from the original manufacturing process
- NDT procedure and results
- Photographs of findings.

C.4 Recommended inspections

C.4.1 Gearbox inspections

The following describe the inspection regime for the gearbox:

- Boroscope inspection of the gearbox to check for teeth condition, for example, cracking, pitting, scoring or fretting
- Visual check of the swarf magnet in the sump (if present)
- Oil analysis to check for particles (if possible, categorisation by size and material), corrosion products, moisture levels and other contaminants

C.4.2 Generator inspection

Most modern turbines will have condition monitoring fitted to the bearings to monitor vibration levels. Where this is not feasible, it may be prudent to visually inspect the bearings, if this is feasible.

- Check all generator mounting and other bolting arrangements are all within specification and tight
- Check the alignment of the generator to the gearbox is within acceptance criteria, ideally provided by the OEM or competent third party
- Visually inspect the colour of grease discharged from the bearings and if variations/particles are visible have the grease analysed to determine the source of the particles
- Visually check the air gap (where feasible) for ingress of dirt/foreign objects
- Visually check the slip ring and brushes for excessive dust/carbon build up. If there is a significant build-up of dust, this must be cleaned
- Inspect all associated cabinets for cable clamping integrity, fuse condition, discoloration of bolted connections and overall cleanliness.

C.4.3 Yaw drives

- Visual check of pinion condition and function check
- Oil sampling and analysis where feasible.

C.4.4 Nacelle condition

External nacelle components: from a safety perspective, the condition of items such as fasteners and other fixings on anemometry frames, hatches and removable covers should be checked, to ensure that these do not create a risk of objects falling.

C.5 Scheduled service (change or prolong existing schedule service)

The following describes service scheduling:

- Review the scope of the scheduled service based on information obtained from modelling, data analysis and the results of the physical inspections. There may be additional items which require proactive replacement or additional monitoring at this time

- Review the evolution over the operation time of the maintenance manual scope to assess the potential effect of removed tasks on life extension
- Adjust scheduled service requirements (for lifetime extension – i.e. after 75% life consumed with and risk analysis uncertainty assessment combined with the component class (as per IEC 61400-1 [N.1]) and combined with the desired lifetime extension duration
- Mitigations following faults detected during inspection are re-entered into the risk analysis (for example, if a fault is detected and repaired, the risk analysis is re-run with this new information).

C.6 Additional inspections and testing

Turbine-specific inspections based on industry knowledge of previous failures to verify load and strength assessment associated with lifetime extension. The scope of these will be specific to the individual site.

For additional testing based on the results of aero-elastic modelling, it may be prudent to carry out metallurgical examination on structural elements, where this is feasible to determine if the degradation of properties is in line with the projections made during the design process.

C.7 Inspection reporting

Following each inspection referred to in Clauses C.3 and C.4 above, the result of the inspection must be thoroughly documented. The inspection report must contain the following information:

- Identification of the turbine inspected
- Date of inspection
- Scope of inspection
- Name of inspectors
- Inspectors company and address
- References to inspector's certification (NDT certification etc)
- Reference to previous inspection reports
- List of specific findings as per Table C.4

Table C.4 – Reporting inspection findings

Tower	Scope of testing (visual and/or NDT including type of NDT) and detected faults should be indicated in a drawing or table. A drawing is preferred Faults (cracks) detected via visual inspection should include information of the crack length. Faults detected via NDT should include information of crack length and maximum depth If previous inspection reports exist, a comparison with these should be made to monitor crack propagation and general health deterioration
Blades	Scope of testing and detected faults should be indicated in a drawing or table. A drawing is preferred Blade erosion should be documented in terms of: location on blade – spanwise and chordwise – suction side or pressure side. The extent of the erosion should be noted in terms of spanwise and chordwise size. Depth of erosion should be noted in terms of exposed material: • Top coat (indicating that leading edge protection has eroded leaving the top coat exposed) • First laminate (indicating that top coat has eroded leaving the first laminate exposed) • Second laminate (indicating that first laminate has eroded leaving the second laminate exposed) • Core material (indicating that all laminate has eroded leaving the core material exposed if core material exists) Detached aerodynamic add-ons (vortex generators, gurney flaps, stall strips etc) should be noted Lightning damage receptors should be noted: • Blackening of material on or around lightening receptors – extent should be noted • Removed material around receptors – extent should be noted • Delamination of blades due to lightening – extent should be noted Results of visual internal blade root inspection should be documented in terms of location and extent of cracks (spanwise and chordwise). Results of internal NDT testing should be documented in terms of location, extent and depth of cracks (spanwise and chordwise). If previous inspection reports exist a comparison with these should be made, to monitor damage propagation and general health deterioration

Table C.4 (cont'd)

Pitch bearings	Inspection for grease leakage, hydraulic oil leakage, loose or missing bolts, cracking of rings, corrosion, wear or damage to pitch mechanism
Yaw ring	Scope of testing (visual and/or NDT including the type of NDT) and detected faults should be indicated in a drawing or table. A drawing is preferred. Fault detected via visual inspection should include information of the type of damage (pitting or cracks) including information of the position, extent and depth (for pitting) of the fault. Faults detected via NDT should include information of crack position, length and maximum depth. If previous inspection reports exist a comparison with these should be made, to monitor damage propagation and general health deterioration
Foundation - onshore	Scope of the inspection of the concrete foundation should be indicated in a drawing or table. A drawing is preferred. If only the visible part of the concrete foundation is inspected, the extent of the visible part of the foundation should be indicated in the report if such information is available. Bolt inspection is documented as stated in the Clause on bolts (further down in this table). If grease cups exist on exterior bolts, the report should contain information about if they are all present, and grease filled. The condition of the sealing between the foundation and the tower should be noted. If sealing is repaired this should be noted
Transition piece and monopile (if offshore)	Scope of testing (visual and/or NDT including the type of NDT) and detected faults should be indicated in a drawing or table. A drawing is preferred. Faults (cracks) detected via visual inspection should include information of the crack length. Faults detected via NDT should include information of crack length and maximum depth. If sacrificial anodes are inspected, the result of this inspection should be noted If previous inspection reports exist, a comparison with these should be made, to monitor crack propagation and general health deterioration
Nacelle frame	Scope of testing (visual and/or NDT including the type of NDT) and detected faults should be indicated in a drawing or table. A drawing is preferred. Fault detected via visual inspection should include information of the crack length. Faults detected via NDT should include information of crack length and maximum depth If previous inspection reports exist, a comparison with these should be made, to monitor crack propagation and general health deterioration
Hub	Scope of testing (visual and/or NDT including the type of NDT) and detected faults should be indicated in a drawing or table. A drawing is preferred. Fault detected via visual inspection should include information of the crack length. Faults detected via NDT should include information of crack length and maximum depth. If previous inspection reports exist a comparison with these should be made, to monitor crack propagation and general health deterioration

Table C.4 (cont'd)

Bolted connections	Scope and extent of inspection should be noted and indicated in a drawing or a table. A drawing is preferred. Type of inspection should be noted: visual inspection, tap testing, re-torquing, re-tensioning, ultrasound If bolts are replaced, serial number and batch number of bolts, nuts and washers should be noted. Type of thread lubrication should be noted
Safety systems	Inspection scope and inspection results should be noted. Safety system maintenance procedures are normally documented in the turbine manufacturers operations manual
Main bearing housing	Scope of testing (visual and/or NDT including the type of NDT) and detected faults should be indicated in a drawing or table. A drawing is preferred. Fault detected via Visual inspection should include information of the crack length. Faults detected via NDT should include information of crack length and maximum depth. If previous inspection reports exist, a comparison with these should be made to monitor crack propagation and general health deterioration
Main shaft	Scope of testing (visual and/or NDT including the type of NDT) and detected faults should be indicated in a drawing or table. A drawing is preferred. Fault detected via Visual inspection should include information of the crack length. Faults detected via NDT should include information of crack length and maximum depth. If previous inspection reports exist, a comparison with these should be made,to monitor crack propagation and general health deterioration
Corrosion	Scope and extent of inspection should be reported. Findings of corrosion should be indicated in a table or a drawing. A drawing is preferred The type of corrosion should be indicated: general corrosion, pitting corrosion, crevice corrosion. In the case of pitting corrosion, the extent and depth of the corrosion should be note along with the inspection method (visual inspection, interferometry) Indirectly detected corrosion should be noted. (i.e. corrosion detected via mis-colouring of material which is thought to stem from corrosion on a hidden surface, for example, a flange connection) Special attention should be given to corrosion on welds and highly loaded structures (for example, on the main shaft, yaw ring, main bearing rings)

Annex D: Analytical assessment of turbine lifetime - relative approach with accuracy assessment [INFORMATIVE ANNEX]

This annex describes an analytical assessment method that considers uncertainties. It is especially suited for the relative approach but may also be adopted (with appropriate modifications) for the absolute approach.

D.1 Sources of uncertainties

There are numerous sources of uncertainties that need to be considered in an analytical assessment of remaining useful lifetime (RUL).

For practical purposes they can be divided into uncertainties related to the analysis model (usually an aero-elastic turbine model) and uncertainties related to the input data to such a model.

To capture those two types of uncertainties adequately in a RUL analysis, the concepts of input data uncertainty U, sensitivity W, model uncertainty M and importance I are introduced. They are explained in the subsequent Clauses.

D.2 Input data uncertainty

It is recommended that the input uncertainty U is divided in four categories (1 = Low to 4 = High).

To assist in the assessment of uncertainty, the uncertainty category may be related to the expected coefficient of variation (CoV) that is defined as the ratio of standard deviation to the mean, see Table D.1. It is strongly advised to limit the uncertainty of data to which the model has high sensitivity to a maximum CoV of 30%.

Table D.1 – Relationship between CoV of data and uncertainty category

CoV	Uncertainty category
< 10%	1
10 to 20%	2
20 to 30%	3
> 30%	4

D.3 Model sensitivity to input data

The model sensitivity is a measure of the influence of input data on the analysis model for the failure mode (and, thus, on the associated lifetime).

For each data item, sensitivity Wi of the input to the analytical model lifetime output is assessed on a scale of 1 to 4, 1 being low sensitivity and 4 being high sensitivity. Whilst detailed sensitivity studies may be undertaken in some examples, it is expected that engineering judgement is most likely to be used based upon experience of running the lifetime assessment model.

D.4 Model uncertainties

Model uncertainty M of the model is a combination of the features of the model, its validation, agreement with load measurements and agreement with inspection reports, known failures etc. The model uncertainty may be different for each failure mode.

The model uncertainty is a measure of both the magnitude as well as (if applicable) the bias of the considered uncertainty source.

The model uncertainty can take one of four levels (1 being low and 4 high). The analyst shall choose an appropriate confidence level and properly document the decision.

The analyst shall validate the model against available data and information and determine the uncertainty M of the model in correctly predicting the validation data. The importance I of accurately predicting the validation data for a specific failure mode shall also be considered.

For each available validation data item ji, model uncertainty Mi and importance Ii shall be categorized into four categories (1 being low and 4 high).

D.5 Uncertainty assessment by Accuracy Assessment Numbers (AAN)

For each relevant failure mode and each (relevant) input data item i the analyst shall assess data uncertainty U_i, model sensitivity W_i.

Additionally, for each available and relevant validation item j the related Importance level I_j as well as the related model uncertainty M_j shall be determined.

The analyst shall give sufficient justification for their choice.

Based hereupon, the weighted data and model uncertainties $\widehat{U}$ and $\widehat{M}$, respectively, shall be computed. They are in the range from 1 (Low) to 4 (High).

Table D.2 - Weighted uncertainty

Weighted data uncertainty	$\widehat{U} = \sqrt{\frac{\sum_i U_i^2 \times W_i^2}{\sum_i W_i^2}}$
Weighted model uncertainty	$\widehat{M} = \sqrt{\frac{\sum_j M_j^2 \times I_j^2}{\sum_j I_j^2}}$

Once these classifications have been established, the overall Accuracy Assessment Number (AAN) is determined from the 4 x 4 matrix shown in Figure 8.

The higher the associated AAN, the less trustworthy are the results of the lifetime assessment Consequently, it might need more backup by appropriate risk mitigation measures such as component replacement/repair, physical inspections, CMS or structural health monitoring.

AAN greater than 12 is unacceptable and steps should be taken to improve the assessment method. Otherwise, the analytical RUL must not be used[1]. Depending upon the value of AAN, limited or detailed inspection is recommended and/or component replacement or repair.

Alternatively, the analyst may try to reduce the weighted uncertainties, for example, by measurements.

[1] Life extension may still be possible based on a risk assessment procedure as described in Clause 6

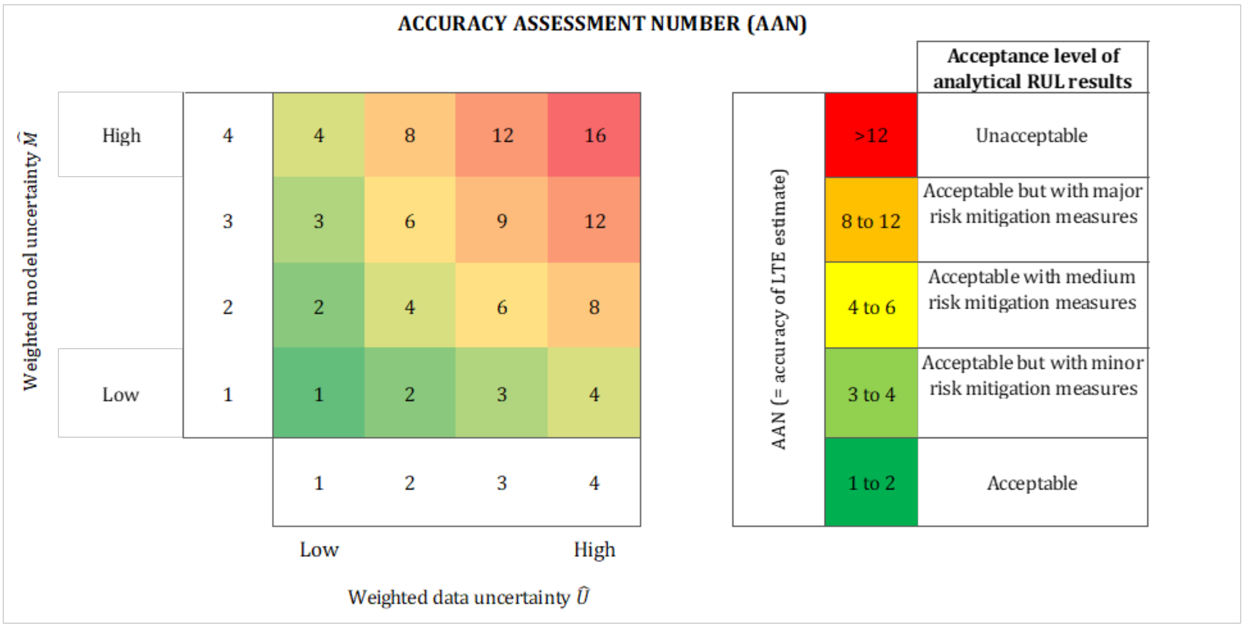
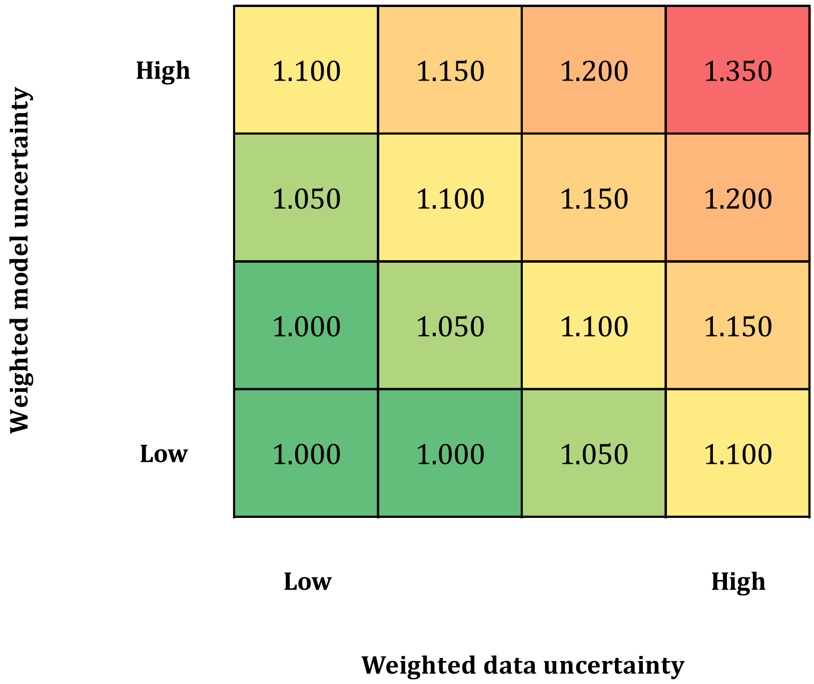


Figure 8: AAN levels



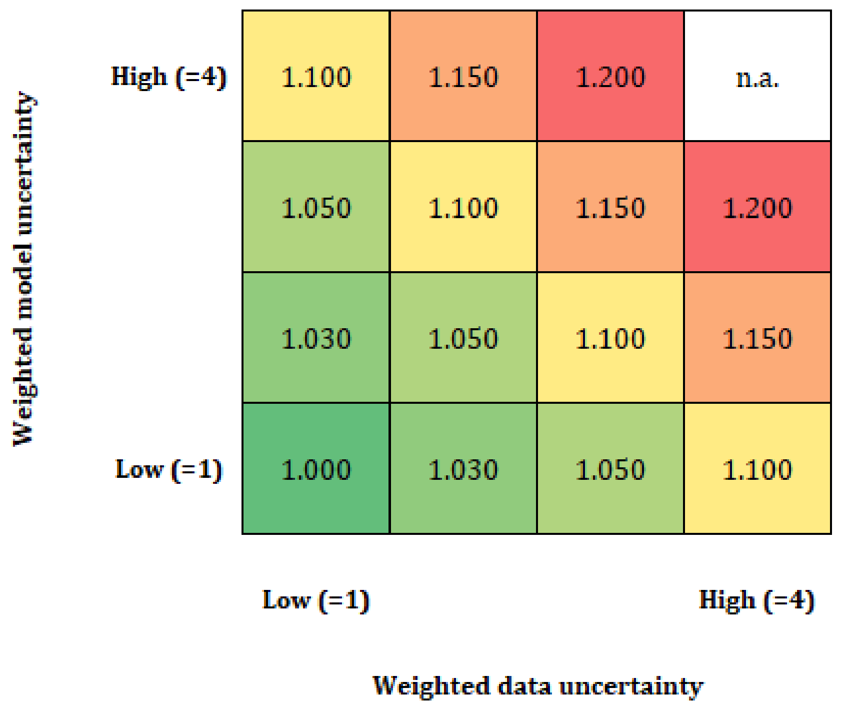


Figure 9: Load increase factors γ depending weighted model uncertainty and weighted data uncertainty

The load increase factors from Figure 9 shall be applied to the relative load level, usually taken as the damage equivalent loads for the site divided by damage equivalent loads under the certified design conditions. The obtained RUL may be taken directly (without additional risk mitigation measures) as an input to the risk management process as described in Clause 6 the (fatigue) loads used to determine it are increased as

$$Loads_{site,increased} = Loads_{site} \times \gamma \qquad (1)$$

with $Loads_{site}$ being the site-specific loads and γ being a safety factor, given in Figure 9: Load increase factors γ depending weighted model uncertainty and weighted data uncertainty.

The safety factors shall be applied to the relative load level, usually taken as the damage equivalent loads for the site divided by damage equivalent loads under the certified design conditions.

D.5.1 Example for the determination of AAN

This Clause gives an example of how the accuracy of results of a relative analysis may be assessed.

Fatigue failure of tower bottom and blade root is investigated based upon a comparison of damage equivalent fatigue loads with appropriate S-N curve slopes.

The assessment of weighted data and model uncertainties is reported in Table D.3 and Table D.4 respectively.

The AAN obtained for the different failure modes of tower bottom fatigue (S-N curve slope m=4), blade root bending edgewise and blade root bending flap-wise (S-N curve slope m=10) are 2 x 3 = 6, 2 x 2 = 4 and 2 x 3 = 6, respectively.

Let the relative load levels be 0.89, 0.96 and 0.91 for the three failure modes.

These values may be used in a risk-based lifetime extension procedure as per Clause 6 if they are multiplied by the corresponding safety factors as illustrated in Figure 9 yielding 0.89 x 1.10 = 0.98, 0.96 x 1.05 = 1.0 and 0.91 x 1.10 = 1.0.

Hence, assuming a turbine design life of 20 years, the respective RUL estimates after 20 years to be used in a lifetime extension process as per Clause 6 are 20 x (0.98^{-4} – 1) = 2 years, 20 x (1.0^{-10} – 1) = 0 years and 20 x (1.0^{-10} – 1) = 0 years.

Table D.3 – Assessment of weighted data uncertainty

Sensitivity: VeryLow:=1 Low:=2 High:=3 VeryHigh:=4
Uncertainty: VeryLow:=1 Low:=2 High:=3 VeryHigh:=4

	Uncertainty	NOTE	TOWER BOTTOM FORE-AFT Sensitivity	BLADE ROOT BENDING EDGEWISE Sensitivity	BLADE ROOT BENDING FLAPWISE Sensitivity
Climate Data					
Turbulence intensity distribution	2	12.7% uncertainty from accredited Laboratory calculations	4	1	4
Air density (remove temperature and humidity because they are entering in air density and ice hours)	1	3.5% uncertainty from accredited Laboratory calculations	3	3	3
Wind rose	1	5.6% uncertainty from accredited Laboratory calculations	4	2	2
Wind speed distribution	3	7.9% uncertainty from accredited Laboratory calculations	3	2	3
Average vertical shear (wind shear)	3	13.2% uncertainty from accredited Laboratory calculations	1	1	4
Up flow (inflow angle)	2	6.8% uncertainty from accredited Laboratory calculations	1	2	2
Special events (negative wind shear, gusts, Ve50 records to be taken into account...)	3	Ve50 events taken into account. No gusts events provided	2	2	3
Operational History					
Actual number of start/stops including emergency	1	Alarms described by the operational team. All years provided	4	1	2
Availability	1	All years provided	3	4	4
Yaw misalignment	4	No yaw misaligment sensors	3	2	3
Ice Accretion	4	No ice accreation reported	1	4	4
Power limit conditions (curtailments, wind sector management, net restrictions...)	1	No limitations	4	3	4
Model Site Specific modifications	2	Specific blade set angle estimated from Power Curve	2	4	4
Materials Data					
Material fatigue curve	1	Materials provided by the client from deisgn information	4	4	4
		Weighted uncertainty	**2**	**2**	**2**

Sensitivity: VeryLow:=1 Low:=2 High:=3 VeryHigh:=4
Uncertainty: VeryLow:=1 Low:=2 High:=3 VeryHigh:=4

	Uncertainty	NOTE	TOWER BOTTOM FORE-AFT Sensitivity	BLADE ROOT BENDING EDGEWISE Sensitivity	BLADE ROOT BENDING FLAPWISE Sensitivity
Climate Data					
Turbulence intensity distribution	2	12.7% uncertainty from accredited Laboratory calculations	4	1	4
Air density (remove temperature and humidity because they are entering in air density and ice hours)	1	3.5% uncertainty from accredited Laboratory calculations	3	3	3
Wind rose	1	5.6% uncertainty from accredited Laboratory calculations	4	2	2
Wind speed distribution	3	7.9% uncertainty from accredited Laboratory calculations	3	2	3
Average vertical shear (wind shear)	3	13.2% uncertainty from accredited Laboratory calculations	1	1	4
Up flow (inflow angle)	2	6.8% uncertainty from accredited Laboratory calculations	1	2	2
Special events (negative wind shear, gusts, Ve50 records to be taken into account...)	3	Ve50 events taken into account. No gusts events provided	2	2	3
Operational History					
Actual number of start/stops including emergency	1	Alarms described by the operational team. All years provided	4	1	2
Availability	1	All years provided	3	4	4
Yaw misalignment	4	No yaw misaligment sensors	3	2	3
Ice Accretion	4	No ice accreation reported	1	4	4
Power limit conditions (curtailments, wind sector management, net restrictions...)	1	No limitations	4	3	4
Model Site Specific modifications	2	Specific blade set angle estimated from Power Curve	2	4	4
Materials Data					
Material fatigue curve	1	Materials provided by the client from design information	4	4	4
		Weighted uncertainty	**2**	**2**	**2**

Table D.4 – Assessment of weighted data model uncertainty

Importance: VeryLow:=1 Low:=2 High:=3 VeryHigh:=4
Uncertainty: VeryLow:=1 Low:=2 High:=3 VeryHigh:=4

Model characteristic describing the aerodynamic, control, structural behaviour	Importance			Uncertainty	Note
	TOWER BOTTOM FORE-AFT	BLADE ROOT BENDING EDGEWISE	BLADE ROOT BENDING FLAPWISE		
Power curve / power coefficient curve	4	1	4	3	Obtained from SCADA
Thrust coefficient curve	4	1	3	3	No measured values to compare. Compared with declared values
Rotor speed vs wind speed	2	2	3	2	Compared and obtained from SCADA
Pitch angle vs wind speed	-	-	-	-	passiv stall -> no pitch
Behaviour of add. pitch features like individual pitch control	-	-	-	-	passiv stall -> no pitch
Behaviour of other control features like Storm Control	-	-	-	-	n.a.
Tower eigenfrequencies	4	1	2	3	Not measured
Blade frequencies flap/edge	2	2	3	2	From design documentation
Drive train eigenfrequencies	1	1	1	1	Measured
Weighted uncertainty	**3**	**2**	**3**		

D.6 Probabilistic assessment of remaining lifetime

In the probabilistic approach, the annual probability of failure is evaluated as function of time using structural reliability methods. A limit state equation is formulated, where uncertainties are modelled directly using stochastic variables. Typically, stochastic variables are included for the following:

- The model uncertainty relating to the application of Miner's rule
- The scatter of test results used to obtain the SN relationship (stress cycle range $\Delta\sigma$, number of cycles to failure, N_f)
- The model uncertainty related to the estimation of component level load effects
- The model uncertainty related to the estimation of the stress concentration factor.

For existing wind turbines, the model uncertainty related to the estimation of component level load effects can be increased or decreased compared to the design situation and this should be included directly in the uncertainty level of stochastic variables. The more type-specific and the better validated an aeroelastic model is, the lower the uncertainty level. The material partial safety factors in IEC 61400-1 ed.4 are calibrated using this approach and a target annual probability of failure in the last year of operation equal to 5×10^{-4}, see [N.28], [I.11], [I.12]. Since the relative cost of safety measures is larger for an existing wind turbine compared to a new wind turbine, using the probabilistic approach it is possible to assess the RUL for a target failure probability higher than 5×10^{-4}, if accepted by relevant authorities [N.28](N.1 Annex K). In cases where inspection of critical failure modes is possible through introduction of periodic inspections, the material partial safety factor may be lowered corresponding to a damage tolerant assessment approach. This is described in K.6 of [N.1]. A recalibration of the safety factor, giving a lower value than the safety factor used for turbine design effectively increases the design capability for the RUL assessment. Given the following two conditions, the reliability model may be updated:

- No cracks or defects are found
- Any defects are repaired adequately.

For welded steel structures, the inspection interval may be set based on a crack propagation growth model to ensure that any crack forming after the previous inspection will not grow to a critical length prior to the next inspection. See example in C4 of [I.11].

Note that when partial safety factors are applied for assessment of the fatigue life, a deterministic, characteristic value equal to the 90% quantile of the turbulence intensity is used in load simulations, whereas in the probabilistic approach, the full distribution of the turbulence intensity is used in load simulations. If deterministic loads are used in a probabilistic analysis, the reliability will be underestimated, as the safety from the use of the characteristic value of the turbulence intensity is not accounted for.

Annex E: Minimal CMDs for rolling element bearings and hydraulic systems [INFORMATIVE ANNEX]

E.1 Preamble

Historically, rolling bearings have caused significant reliability issues. With the advent of sophisticated pitch systems to control dynamic loads on blade, main shaft and gearbox bearings (as well as structural loads on the tower and nacelle), pitch bearings are subjected to increased cumulative angles of oscillation under high loads compared to earlier designs. For pitch and yaw bearings, earlier designs suffered inappropriate operating conditions for ball bearings due to quasi-static operation under high loads with very small movement making lubrication almost impossible. This is in addition to the high uncertainty about real loads in operation.

There are many issues to be dealt with to assess bearing health and real lifetime during through-life management and to examine the technical risks and commercial returns associated with life extension, one of which is the continuing performance, reliability and life of the many rolling bearings used in wind turbines. For any stakeholders, these risks must be evaluated against safety considerations, the cost of monitoring and remediation of failed bearings and the potential commercial returns. There are also considerations of accessibility, availability of specialist equipment and spares, as well as the appropriate season to minimise outage costs.

The accuracy of risk predictions of bearing failures during and beyond design life are dependent upon the quality of data used for such analysis and the methodologies employed to assess the risk (or probability) of failure at any time/age in operation. From the outset it must be emphasized that it is not possible to predict the time of failure of an individual bearing in an individual wind turbine. Only current health can be certain together with an estimation of the probability of failure of that bearing within a population.

From commissioning onwards, condition monitoring systems (CMS) such as grease and oil analyses (particle identification, sizing and counting), vibration monitoring, temperature monitoring, yaw and pitch motor current analysis and hydraulic cylinder pressure vs speed, amongst others, allow detection of early degradation of bearing health.

This also means that exchanging a bearing arising from an analytical prediction, without visible damage or reliable condition monitoring indications, results in a high probability that the bearing will be unfailed and thus removed unnecessarily. This is because analytical predictions are in the form of probability of failure vs time and the emphasis is on those bearings expected to fail within the L10 life estimate (thus 90% are expected to survive).

Bearing life estimation models such as ISO 281 [I.6] or ISO 16281 [I.22] (used for the design of wind turbine rolling elements according to IEC 61400-1 §9.8 and gearboxes according to IEC 61400-4 [I.23]) give a probabilistic view of the failure rate of similar bearings in similar applications as a function of time. Typically, a minimum L10 life of 20 years is specified for each bearing in a gearbox. Since there may be in excess of 20 bearings in a drivetrain, series reliability is of importance because failure of any single bearing renders the drivetrain inoperative. The L10 life of each bearing should be much greater than 20 years in order that the target system life is achieved.

Furthermore, assumptions may be incorrect. For example, calculations are typically based on "slight to typical" contamination for oil and grease, but as there is no standard for grease cleanliness, most of the time grease analyses are not carried out (except when it is already known that the pitch bearing or the main bearing is badly damaged). Experience shows that when analyses are done, the hard particles content and sizes, as well as the water content are much too high compared to good practices in other industry sectors. For gearboxes, the wind industry common practice is to keep in operation a degrading component as long as possible. It is clear that hard particles emitted by this degrading component will undoubtedly induce micro-dents or indentations and scratches in other components by the time the oil carries those particles away to the filter. Then this practice which is not even saving money on the repair itself but just delaying it a few months, may also reduce the life of the full gearbox and increase the expense of overhaul much higher than any savings.

For the drive train as a system, timely replacement of suspect bearings up-tower gives only a marginal improvement in probability of failure (POF) of the system. Furthermore, secondary damage of components from hard particles leads to an increased risk of repeated failures.

E.2 Bearing failure modes

The bearing life estimation method ISO 281 [I.6] (as embodied in, for example, IEC 61400-1 §9.8 and IEC 61400-4 [I.23] for gearboxes) only covers sub-surface and particulate initiated (surface) fatigue and there are many known failure modes that afflict wind turbine bearings, for example:

- Adhesive wear
- Abrasive wear
- Smearing
- Axial cracking
- Micro-pitting
- False brinelling
- Indentation damage
- Corrosion
- White etching cracking and white structure flaking (WEC/WSF)
- Geometric stress concentration fatigue
- Particulate damage surface fatigue
- Cage fracture.

No validated life estimation models have been developed for any of the above failure modes, possibly with the exception of particulate damage surface fatigue (covered in ISO 281 [I.6]). This is due to a lack of understanding of the mechanisms at play and the influencing parameters. In any case, if such models were to be developed and fully validated against service experience, they could only predict the probability of failure (POF).

E.3 The pragmatic approach

Stakeholders will inevitably balance the potential returns from facing outages due to unexpected failures as part of through-life management and running a wind turbine beyond its design life against the cost of enhanced inspection/condition monitoring regimes, any remedial or upgrade actions and the life extension exercise itself.

A pragmatic approach may therefore consist of:

- Evidence from maintenance, inspection and condition monitoring that will detect as early as possible, the potential onset of bearing failure during through-life management
- Evidence from the wind turbine manufacturer on theoretical reliability levels for components and systems, highlighting those which are most likely to have the highest POF (recognizing the limitations of the inevitable differences in site conditions from those assumed in design)
- Evidence from field experience on reliability and maintenance histories on similar turbines or wind farms (but considering the limitations that operating conditions on bearings must be similar and bearing types equivalent)

- Assessment, based on a transparent root cause analysis and a calculation of additional life under real operational loads for the specific site comparing the repair solution with the failed solution.

NOTE For future designs, it is recommended the OEM increases the safety margins in design for those bearings to match the greater uncertainties in operation conditions (eg lubricant cleanliness, starts and stops with poor lubrication, low and high temperature operations, mixed elasto-hydrodynamic lubrication regimes, oscillatory motion unfavourable to rolling bearing designs).

E.4 VMS

Most of existing VMS are based on proprietary systems sorting, filtering and analysing the vibration data locally and delivering pre-analysed information based on pre-set thresholds. The alarms must be reviewed by a competent expert who will integrate the fault progression rates, the context either to reset the threshold or to deliver a prognosis, potentially a RUL estimation and action advice. If detection and fault progression monitoring is almost 100% reliable when combined with lubricant wear particles analysis, as explained above, prognosis on RUL and Failure moment may be unreliable for some of the failure modes.

A vibration-based monitoring system may detect the following:

- Spalling of rolling bearings raceways
- Spalling of gear teeth
- Cracks in gear teeth
- Cracks in bearing rings
- Early wear of bearing raceways
- Early wear of gear teeth
- Indentations on gear teeth
- Indentations on bearing raceways
- Imbalance of shafts or gears due to poor assembly or misalignment
- Imbalance due to gear manufacturing faults
- Incorrect clearances of bearings or gears
- Failures in the lubrication system
- Failures in cooling fans
- High speed shaft coupling Failure
- Changes to wind turbine structure due to weld cracking or loosening fasteners.

A vibration-based monitoring system requires the following measurements:

- Vibration of each gearbox stage
- Vibration of all main bearing(s)
- Vibration of each of the generator bearings
- Vibration of the tower and nacelle
- Vibration of each of the blades
- Vibration within main frequency bands for bearings of high-speed parts
- Low-frequency acceleration or motion of bearings of the low-speed parts
- Operational conditions: wind speed, power, rotation speed.

Acceptable values are depending on specific design, manufacturing and are more considered in a relative way by deviation from the commissioning status.

At the current state-of-the-art, VMS is not effective on yaw bearings or pitch bearings.

E.5 Temperatures

Acceptable values are dependent on specific design, manufacturing and operating conditions of the considered component. Excessive temperature is considered by deviation from the commissioning status, or by comparison with neighbouring turbines with same or similar component, taking in account operational and ambient conditions.

When a deviation is identified, an expert should analyse the probable cause(s) by correlating with other CM data (VMS and wear particles in lubricant) and advise for inspection and preventative or corrective actions.

Temperature deviation is very often the latest stage of the fault of a high speed bearing or even a main bearing before failure. This does not apply to yaw bearings and pitch bearings.

NOTE Temperature monitoring is mainly applied for bearing and lubricants. It will not be efficient on yaw bearing and pitch bearings. It may also apply to windings in motors and generators as well as electrical cabinets, electro-mechanical components and electronics when available

NOTE over greasing may induce a higher temperature during a short period of operation.

E.6 Grease cleanliness

Samples of grease should be taken from the active part of the bearings (for example, between rollers and not on the sides) with care to avoid external contamination, after similar operation periods and prior re-greasing (if re-greasing is not automatic).

The following parameters shall be measured and recorded in grease analysis:

- Wear particles - Induction Coupled Plasma-Atomic Emission Spectrograph (ICP-AES) or Optical Emission Spectrography (OES). Particles are analysed for wear: iron Fe, chromium Cr, tin Sn, aluminium Al, nickel Ni , copper Cu, lead Pb, manganese Mn, PQ Index; Direct reading ferrography (a specific process able to identify visually size and count of magnetic particles in a prepared sample, differentiating between small <about 6µm and large); Scanning Electron Microscope analysis (helps to visually identify nature and size of most of particles in a sample)
- Contamination and additives (specific investigations for comparison with original chemistry of grease)
- Infrared spectrum
- Water content (e.g. using Karl Fischer method)
- Oil separation (bleeding) characteristics

NOTE PQ index is a specific methodology given a ratio for magnetic particles to define fault type

- There is currently no standard for grease cleanliness
- If possible, implement size measurement and count of particles in lubricant from commissioning to ensure best lubrication and allow early detection from trends.
- Hard particles larger than the lubricant film thickness (usually around 10 to 15µm as an order of magnitude under hydrodynamic conditions) will significantly reduce lifetime (ISO 281:2007 [I.6] up to 90% life reduction) when being crushed between raceways and rolling elements. It should be avoided from commissioning.
- High particle count during early run-in period is not acceptable and might:
    - shorten the lifetime of the component even if the count reduces afterward by purging;

- cause crushing of hard particles even for a short period of time which will induce micro-dents and micro-cracks in the hardened layers of the raceways that will develop slowly afterward (years) under fatigue process: no mitigation is possible;
- increase the crushing effect even for smaller particles because hydrodynamic conditions may not be reached due to very low speed and/or to very small motion for main bearings, pitch bearings and yaw bearings.

- Bearings must have a good finish and cleanliness from manufacturing, workshop assembly, commissioning and during operation
- Lubricant should be as clean as possible at any time

As a reference, grease analysis result thresholds that might give indication about early wear and tear as given below. Note that those values are not absolute but order of magnitude. Consider also trends as major indicator of fault:

- Iron content (to be correlated with particle sizes, chromium content and VMS):
  - up to 100 ppm: good
  - from 100 to 500ppm: to be monitored and correlated with VMS
  - from 500 to 5000ppm and trending up over time: on going Fault (if correlated with 1 to 3% chromium bearing steel)
  - above 5000ppm check temperature monitoring and other appropriate parameters for a proper change/exchange decision
- Hard particles sizes:
  - PQ index:
    - below 25: Ok
    - over 25 and trending up: warning fault ongoing
  - Ferrography or scanning electron microscopy (SEM) to measure, identify and count potentially large particles (above 10µm). If large hard particles can be identified, remaining useful life (RUL) should be calculated with “severe contamination” instead of “slight to typical” (ISO 281:2007 [I.6]) but this is limited to probability of failure

E.7 Oil lubricant cleanliness (acceptable values over whole lifetime)

Sampling of lubricant oil should be performed according to the procedure defined in ISO 4021:1992 [I.5] and according to the gearbox or hydraulic system O&M Manual.

The following parameters shall be measured and recorded in lubricant oil analysis:

- Viscosity
- Moisture and water
- Acid number
- Additives
- Cleanliness (ISO 4406:1999 [I.4])
- Wear particles (ICP-AES or OES). Particles analysed for wear: iron Fe, chromium Cr, tin Sn, aluminium Al, nickel Ni, copper Cu, lead Pb, manganese Mn, PQ index (PQ index is a methodology specific to the OilCheck company, given a ratio for magnetic particles to define fault type)
- Direct reading or analytical Ferrography

Typical figures, based on ISO 4406 [I.4], for common lubrication systems are shown below.

In lubrication systems, contamination with metal is mainly from internal sources (for example, early wear or spalling).

For gearbox:

- with ball bearings 15/13/10
- with roller bearings 16/14/11
- with journal bearings 17/15/12

For hydraulic systems:

- with proportional valve and for cylinders
  - 17/15/12 below 140 bars
  - 16/14/11 from 140 to 212 bars
  - 15/13/10 above 212 bars
- without proportional valves or cylinders
  - 18/16/13 below 140 bars
  - 17/15/12 above 140 bars

Cleanliness has an effect upon the expected lifetime (independent of which company is supplying the filters). Typical examples of ISO codes are shown in Table E.1.

Table E.1 - Examples of ISO codes

Roller Contact Bearing

Current ISO Code	Target ISO Code	Target ISO Code	Target ISO Code	Target ISO Code
	2 x Life	3 x Life	4 x Life	5 x Life
28/26/23	25/22/19	22/20/17	20/18/15	19/17/14
27/25/22	23/21/18	21/19/16	19/17/14	18/16/13
26/24/21	22/20/17	20/18/15	19/17/14	17/15/12
25/23/20	21/19/16	19/17/14	17/15/12	16/14/11
25/22/19	20/18/15	18/16/13	16/14/11	15/13/10
23/21/18	19/17/14	17/15/12	15/13/10	14/12/9
22/20/17	18/16/13	16/14/11	15/13/10	13/11/8
21/19/16	17/15/12	15/13/10	13/11/8	-
20/18/15	16/14/11	14/12/9	-	-
19/17/14	15/13/10	13/11/8	-	
18/16/13	14/12/9	-	-	
17/15/12	13/11/8	-	-	
16/14/11	13/11/8	-	-	
15/13/10	13/11/8	-	-	
14/12/9	13/11/8	-	-	

Laboratory and field tests prove time and again that Hy-Pro filters consistently deliver lower ISO fluid cleanliness codes.

Improving fluid cleanliness means reduced downtime, more reliable equipment, longer fluid life, fewer maintenance hours, and reduces costly component replacement or repair expenses.

Hydraulic Component

Current ISO Code	Target ISO Code	Target ISO Code	Target ISO Code	Target ISO Code
	2 x Life	3 x Life	4 x Life	5 x Life
28/26/23	25/23/21	25/22/19	23/21/18	22/20/17
27/25/22	25/23/19	23/21/18	22/20/17	21/19/16
26/24/21	23/21/18	22/20/17	21/19/16	21/19/15
25/23/20	22/20/17	21/19/16	20/18/15	19/17/14
25/22/19	21/19/16	20/18/15	19/17/14	18/16/13
23/21/18	20/18/15	19/17/14	18/16/13	17/15/12
22/20/17	19/17/14	18/16/13	17/15/12	16/14/11
21/19/16	18/16/13	17/15/12	16/14/11	15/13/10
20/18/15	17/15/12	16/14/11	15/13/10	14/12/9
19/17/14	16/14/11	15/13/10	14/12/9	14/12/8
18/16/13	15/13/10	14/12/9	13/11/8	-
17/15/12	14/12/9	13/11/8	-	-
16/14/11	13/11/8	-	-	-
15/13/10	13/11/8	-	-	-
14/12/9	13/11/8	-	-	-

Develop a Fluid Cleanliness Target

Hy-Pro will help you develop a plan to achieve and maintain target fluid cleanliness. Arm yourself with the support, training, tools and practices to operate more efficiently, maximize uptime and save money.

Annex F: Example of a methodology for assessment of risk [INFORMATIVE ANNEX]

F.1 Overview

This annex describes a suggested method for assessing risk and identifying where risk controls need to be adapted during the operating life of an asset, in order to maintain a tolerable level of risk. The method is based on two key concepts:

- Using failure modes and effects analysis (FMEA) to calculate a risk priority number (RPN) for identified failure modes of the primary structural elements of a WTG
    - While many risk assessment processes are available, calculating an RPN includes assessing the ability to detect a failure mode before failure occurs, which is important when making decisions about life extension and inspection and maintenance regimes
    - The potential for the RPN to increase over time should be assessed, and if it is identified that the RPN will exceed a tolerable level, mitigation should be applied
- If the mitigation depends on a regime of inspection and monitoring to detect deterioration that could lead to catastrophic failure, then the effectiveness of the regime should be assessed, with respect to its ability to detect the early stages of failure in sufficient time to allow action to be taken to prevent a catastrophic failure. This is described further in Clause F.3 below.

F.2 Application of failure modes and effects analysis

Full details of FMEA are given in IEC 60812:2018 [N.16] Failure modes and effects analysis (FMEA and FMECA). Only the most relevant points are described here.

The risk priority number (RPN) is the product of semi-quantitative values for severity (S), occurrence (O) and detectability (D). Each of these is assigned a value from 1 to 10 for each identified failure mode:

- High values of S indicate high severity
- High values of O indicate high probability/ frequency
- High values of D indicate a high probability of the failure mode *not* being detected

Possible RPN values therefore range from 1 to 1000; as the RPN values from a particular FMEA study depend on the criteria used for determining values of S, O and D, it is not valid to compare RPNs between studies, or to set a single limiting value to be applied to different studies. Annex B.4 of IEC 60812:2018 gives an example of how S, O and D could be defined for a FMEA study on a wind turbine. Where there is uncertainty in estimates of S, O and D, then a conservative approach should be taken; if this results in a high RPN, then it may highlight where additional work could reduce uncertainty and hence justify claiming a lower RPN.

Note that in this document, the term RPN is used. It has been assumed that a logarithmic scale would typically be used for estimates of the probability of occurrence. This philosophy is common amongst implementations of FMECA. In IEC 60812, this formulation is described as the ARPN (alternative risk priority number).

Considering each of these over the lifetime of a wind turbine:

- Severity S is likely to be constant, unless changes have occurred that increase the consequences of a failure, such as if the area around a WTG is developed for industrial activities or infrastructure
- Occurrence O is likely to increase over time, due to deterioration such as fatigue or corrosion. Estimates of occurrence may be informed by:
    - analytical work (including calculation of Site-Specific Expected Life/Remaining Useful Life)
    - fleet knowledge, such as history of inspection findings or experience with similar WTGs

- Detectability D depends on the inspection and monitoring regime, which the operator of the wind farm can determine. This could include approaches such as:
  - failure modes will have low values of D when relevant parameters are only monitored through SCADA or protective systems, that will raise an alarm or trip the WTG
  - for example, while sudden seizure of a main bearing might result in a structural failure, such a seizure is very likely to be preceded by a rise in bearing temperature, for which a simple protective system could stop the WTG before seizure occurred
  - failure modes that are only detected through periodic intrusive visual inspection are likely to have high values of D.

An example of this is illustrated in Figure 10 and Figure 11 below which show how increasing occurrence O can cause RPN to increase over time. If this results in the RPN exceeding a tolerable level, then improving detectability may bring the RPN back below the acceptable limit.

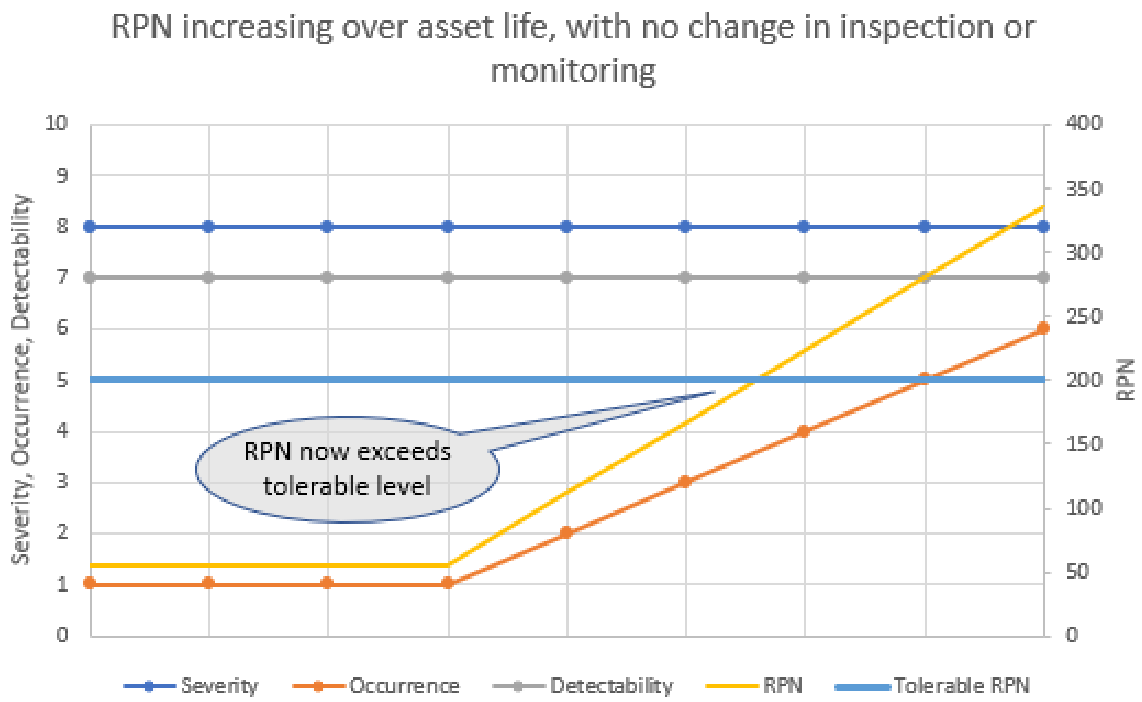


Figure 10: Illustration of RPN increasing in later life due to increasing occurrence.

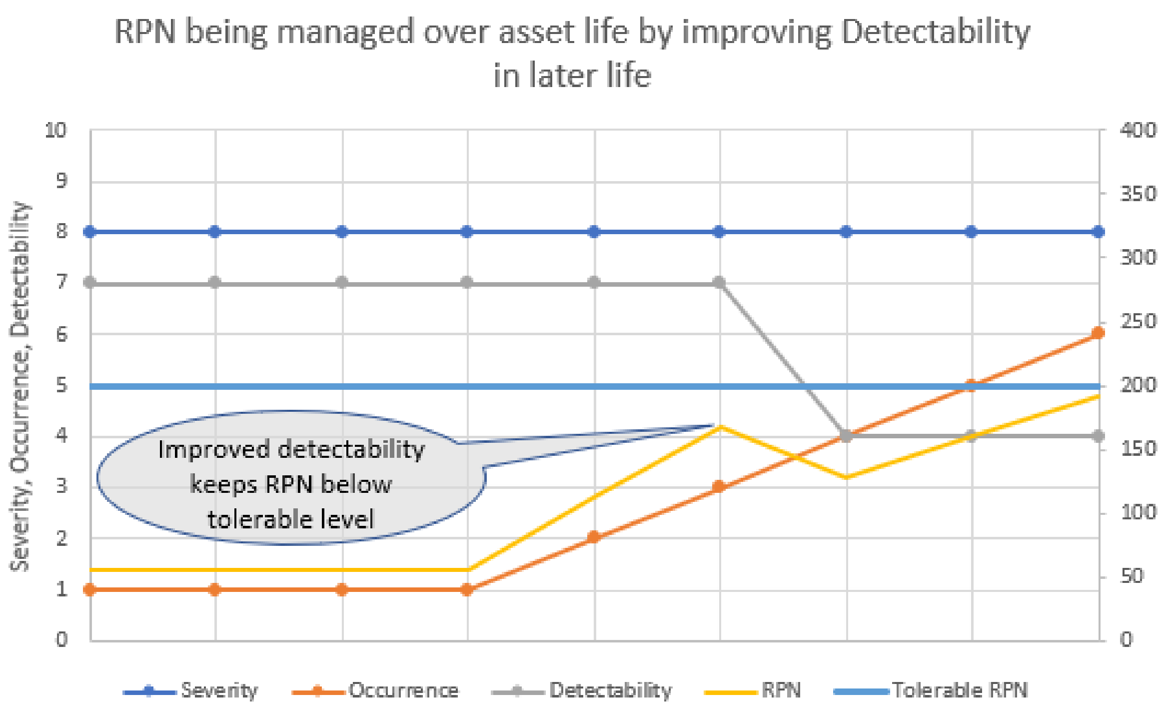


Figure 11: Illustration of managing RPN by improving detectability in later life.

Note that even if estimated values of O are very low, such as in early life when the calculated probability of failure is very low, sufficient inspections or monitoring should still be undertaken to detect failures that cannot be predicted from analysis, such as those that might arise from deficiencies in site conditions assessment, design or component /assembly quality.

F.3 Using the potential failure (P-F) interval to assess detectability

IEC 60300-3-11:2009 *Dependability management – Application guide – Reliability Centred Maintenance* [N.14] defines potential failure as an "identifiable condition that indicates that a functional failure is either about to occur or is in the process of occurring". For example, a short crack identified in an item may be the potential failure state indicating that if no action is taken, functional failure of the item can be expected to occur.

The standard also defines the potential failure (P-F) interval as being "the interval between the point at which the degradation becomes detectable and the point at which it degrades into a functional failure". If it is proposed to rely on detection to reduce the risk of a structural failure occurring, then several criteria, defined in the standard, shall be satisfied. These include those in the following list:

- The condition shall be detectable
- The deterioration shall be measurable
- The P-F interval shall be long enough for the condition monitoring task and actions taken to prevent functional failure to be possible
- The P-F interval shall be consistent.

While these may be demanding criteria, there is little benefit in operating a regime of inspections or monitoring, unless the method and frequency applied are effective in reducing the risk of catastrophic failure. The regime could be optimised by approaches such as:

- Analytical (and possibly measurement) work, to identify priority areas of the structure, so that effort can be targeted efficiently

- Fracture mechanics, to determine the size of defect that needs to be detected (i.e. the potential failure) and predict how long this gives before failure (i.e. the P-F interval)
- Selection of appropriate inspection and monitoring techniques, that are capable of detecting the potential failure.

The interval for the inspection or monitoring activity should be less than or equal to the P-F interval; establishing this requires both an understanding of the effectiveness of the inspection or monitoring activity, and the rate of deterioration. Knowledge of the P-F interval can help to determine the appropriateness of inspection and monitoring techniques. For example, if the blades of a WTG are estimated to have high occurrence O values, and if achieving a satisfactory detectability D value will require regular internal inspections (with significant cost implications), then moving from relying on inspection, to increased monitoring (such as retrofitting a blade condition monitoring system) might be a better economic and technical solution.

F.4 Summary

When assessing risks relating to operation of wind turbines, and particularly in relation to life extension, it is important to consider the ability to detect the early stage of a failure, before it could result in a hazardous functional failure. Various risk assessment approaches take account of this.

The technique suggested here involves calculation of RPN, as part of an FMEA study, to provide an estimate of risk, which takes account of the ability to detect the failure. While there may be little scope to alter the severity or occurrence of a failure, the level of risk as expressed in the RPN can be modified by changing the detectability of early stages of a failure.

Detectability depends on the regime of inspection and monitoring that is implemented. Its effectiveness should be reviewed against the potential failure interval of relevant failure modes, with the aim being that the inspection or monitoring activity is carried out at a shorter interval than the potential failure interval, so that deterioration is detected before functional failure occurs.

Annex G: Through-life management and remaining useful life [INFORMATIVE ANNEX]

G.1 Through-life management

The owner/operator may need information or technical support during operation from the OEM, third party operator, ISP for maintenance, in-house maintenance team, independent expertise and specialized laboratories in order to achieve a proper through-life management process.

It can be stated that through-life management (TLM) will continue during a period of extended operation. However, it should be emphasised that any assessments of current health of components will be based upon the failure risks (including both probability of occurrence and consequences). It is therefore for the wind farm owner, operator and other stakeholders to judge what level of risk is acceptable for continued operation.

Figure 12 shows TLM for a wind farm, whilst Figure 13 applies to a wind turbine. Figure 12 is appropriate to through-life management according to the current technical specification.

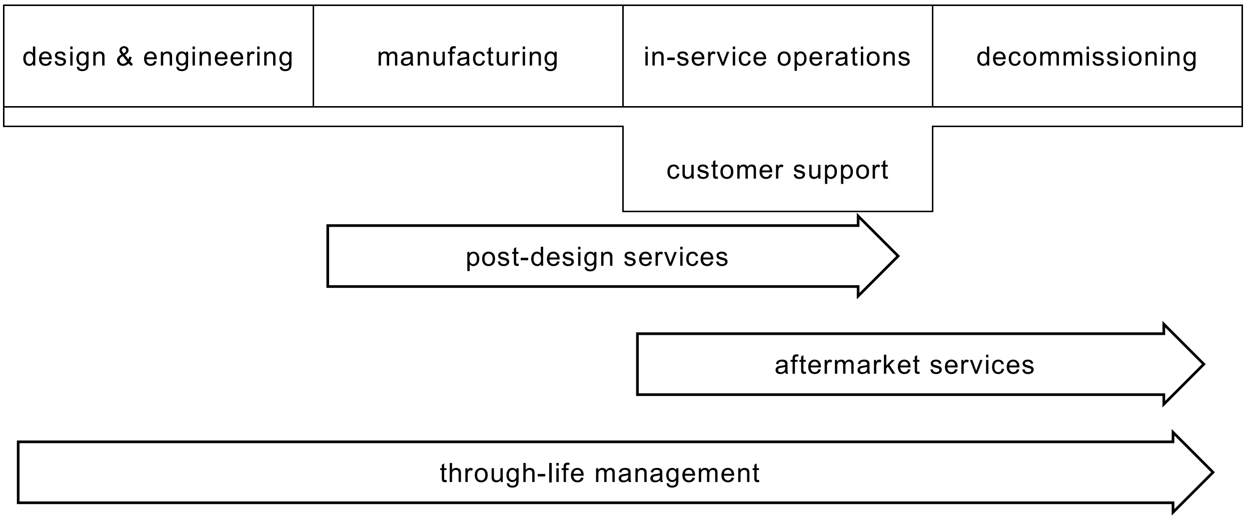


Figure 12: Through-life management of a wind farm

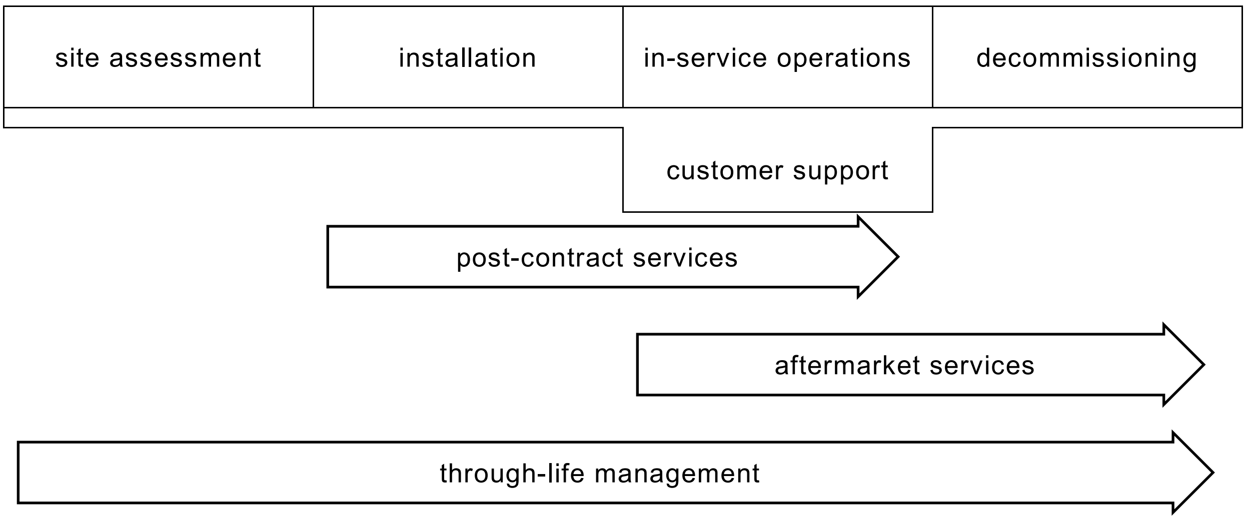


Figure 13: Through-life management of a wind turbine

Through-life management should be based on the following inputs:

- Information about the site (information prior to construction, subsequently updated)
- Information about the site assessment for loads and structural integrity, typically by the OEM resulting in Site Specific Assessed Life (including uncertainty)
- Information about processes (and loads particularly) related to transport of components to site, on-site construction, commissioning)
- Information about the turbines (for example, from the OEM regarding delivered materials, parts, conditions of certification, CMS, model parameters for estimating RUL)
- All the genuine O&M manuals for the turbine from the turbine OEM and for the specific Structural Components from each component OEM
- Remote diagnosis (for example, experience with CMS, false positives, false negatives)
- Predictive algorithms
- Maintenance records (for example, tasks performed, parts exchanged with genuine brand, serial number and type from the component OEM with potential upgrades on detailed explanation about what was improved by the upgrade, access to turbines)
- List of all the sensors, accuracy of the signal, how data are collected, retained, quality checked, retrieved, processed and what insights are learnt (such as site characteristics, load time series, WTG model parameters)
- Scheduled maintenance tasks – for example, major part replacements, potential upgrades on the replaced components and detailed explanation about what was improved by the upgrade, site-visits for inspections, NDT
- Document control, staff training
- Decommissioning and disposal procedures, weight and nature of the different materials included in each major component
- Insights from all of the above
  - such as using historical records to estimate normal conditions
  - rates of fault with regards all modes of failure, current health of components
  - future expectations regarding fault, enabling estimates of RUL
  - enabling the planning of particular maintenance tasks
  - capacity for continued operation (and on what basis – for example, curtailment, limited wind directions, increased inspections, new CMS, operation under conditions of reduced turbulence)

G.2 Life extension

Life extension is the period of site-specific life that under measured site conditions and best maintenance practices will be in excess of one of the following periods:

- Type certified design life (site suitability to turbine type class assessed at procurement stage)
- Site specific assessed life set at procurement stage after site assessment

Life extension must be supplemented by an activity to underwrite continued safe and reliable operation of a wind turbine beyond its type certified design life or site-specific assessed life, respectively. The period of life extension will depend upon whether a detectable fault has already occurred or not, and if RCA shows a potential serial effect on the site or not. In the former case, RUL estimates for individual components or structures may assist.

Where no detectable fault has occurred, the period of life extension will be based upon the probability of failure (and associated uncertainty) determined by modelling, enhanced by inspection and/or condition monitoring, with stakeholders deciding upon the level of acceptable risk as time progresses.

There are some scenarios relating to life extension. Design damage accumulation will be subject to a safety margin over the actual damage accumulation. The former uses a design fatigue curve whilst the latter the actual fatigue curve. Both have bands of uncertainty arising from the fatigue data and assumed loads.

Both may be revised during operation based upon the actual wind loadings compared to design assumptions.

Some scenarios have been illustrated in Figure 14, in which the life may be understood as the minimum value of life of all primary components:

a) T2 = Site Specific Assessed life (SSAL). Life extension of L2 is permissible because damage limit is reached at T1 (over-design case)

b) T1 = Site Specific Assessed Life (SSAL). Life extension of L3 is permissible but with caution. Safety margin S3 against failure is reduced. Periodic inspection for the appearance of damage will be necessary together with load monitoring

c) T1 = Site Specific Assessed Life (SSAL). Life extension to T4 is not permissible because the safety margin S4 is unacceptably small

d) Design Life = 20 years (wherever on the graph below): In certain countries, specific procedures may be necessary for legal reasons to extend the permit to operate.

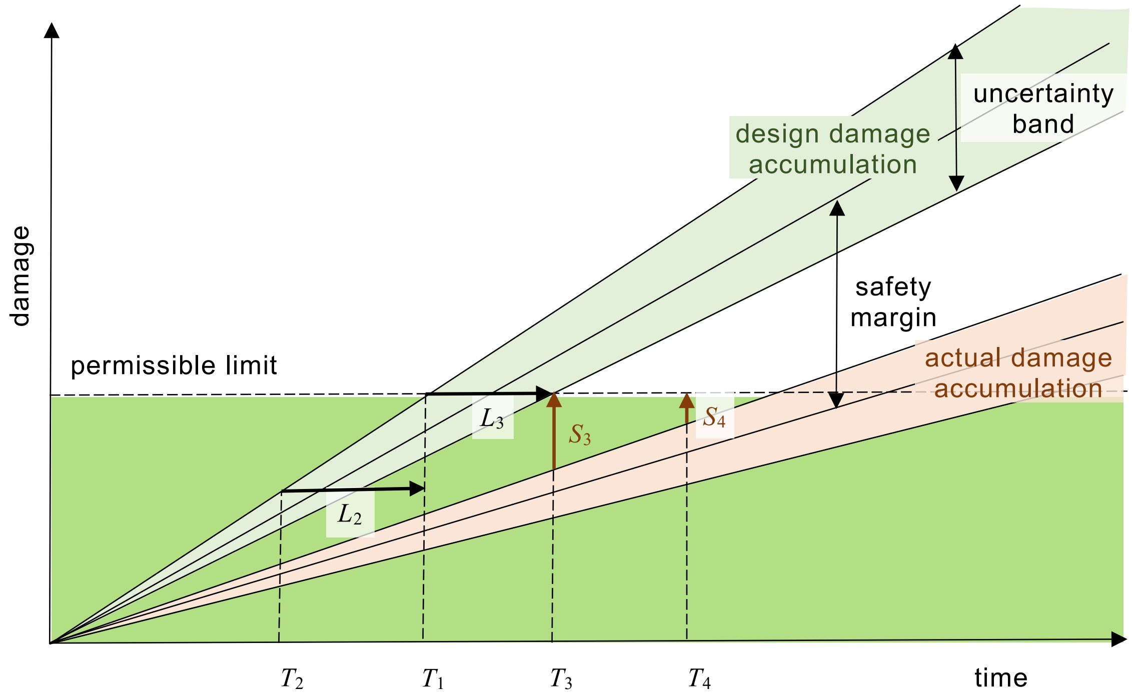


Figure 14: Life extension scenarios

G.3 Remaining useful life

Throughout the life of a wind turbine/wind farm, there will be a slight decline in the condition of a component or system until a point is reached at which the first signs of impending failure are seen (a symptom). Diagnostics will indicate the likely cause(s) of the problem, whilst prognostics attempt to estimate the time to functional and catastrophic failure when safety would be compromised, termed the remaining useful life (RUL). Note that estimates of RUL will be subject to differing levels of uncertainty depending upon the quality of data available and quality of assessment methodology.

Below are three cases of how Site-Specific Expected Life (SSEL) differs from Site Specific Assessed Life (SSAL) and how the permissible RUL can be obtained whilst observing the uncertainty (in modelling and observation) and including an appropriate safety margin.

Case 1: Single component with no failures *(*Figure 15*)*

In this case, a single component is considered. At the time of the project certification the Site-Specific Assessed Life (SSAL) is determined – shown as a dotted yellow curve. However, the component does not deteriorate as fast as predicted/projected but follows the blue curve. This could be due to more benign site conditions than assumed in the SSAL. At a point in time, an assessment of the RUL is done (via inspections, site assessments, load assessments and other methods). It is then revealed that the component is in better health than predicted, and that it deteriorates at a slower rate (the green dotted curve). Using this assessment, the Site-Specific Expected Life (SSEL) is estimated. Due to uncertainty in the model and the available data, an error band is assigned around the updated deterioration curve. Further, an appropriate safety margin is applied, and permissible RUL can be determined.

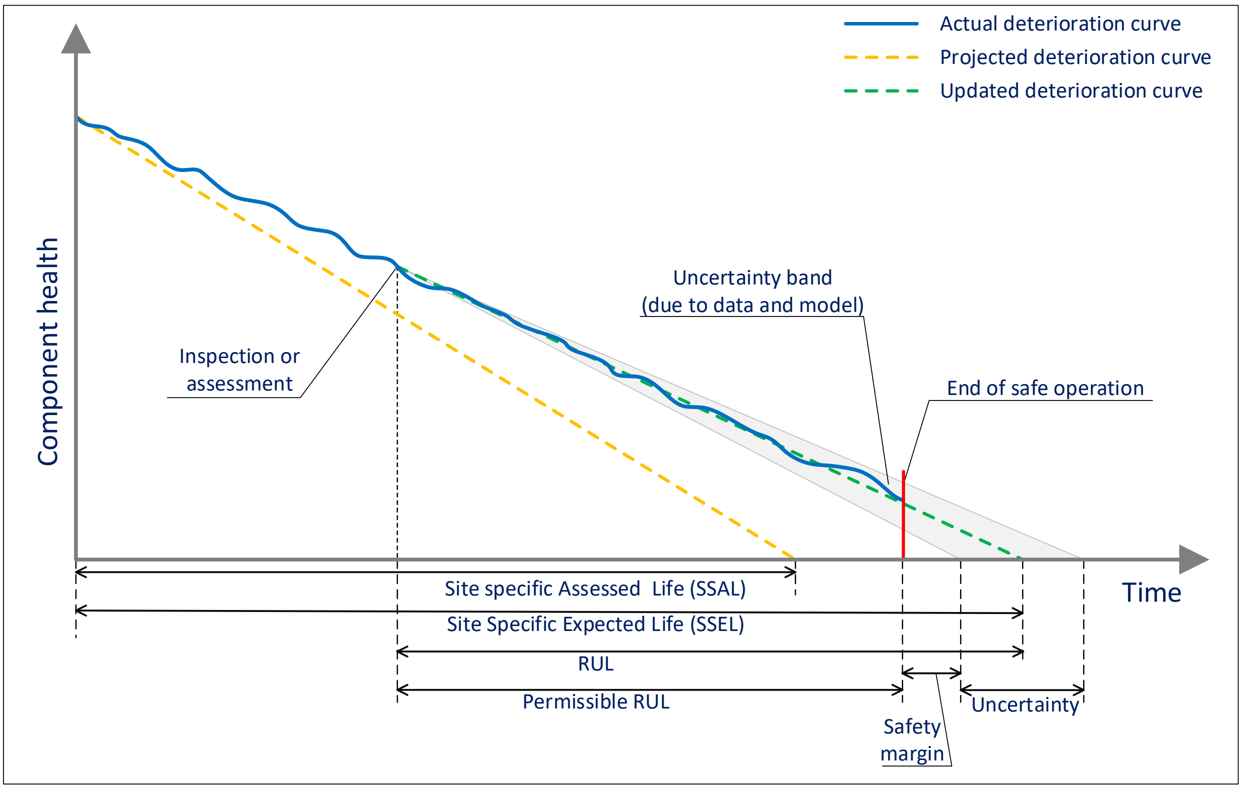


Figure 15: Single component with no failures

Case 2: Single component with symptom (Figure 16)

Like in Case 1, a single component is considered. Again, the SSAL assumes that the component deteriorates along the yellow dotted line, whilst, in reality, the component follows the blue line for the most part. After some time, a symptom occurs prematurely on the component. The symptom, if left unattended, would result in a steeper deterioration curve (the brown dotted line). The symptom is rectified, either via repair or replacement of the component, leading to the vertical shift in the blue line. It may not be possible to restore the pre-fault condition entirely, especially in the case where the component is repaired and not replaced, which is why, in the figure, the blue line follows below the original trajectory. After the repair, the RUL estimate is updated similarly to case 1, and the new permissible RUL can be determined.

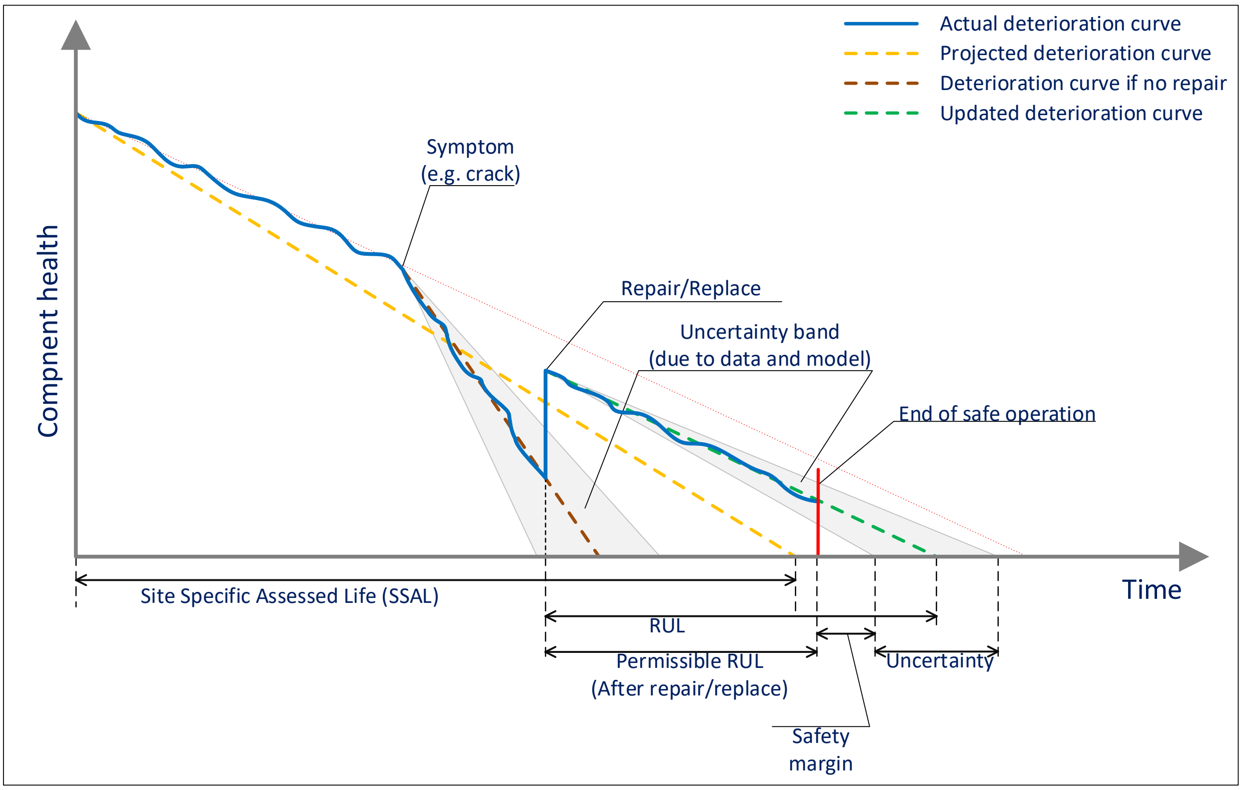
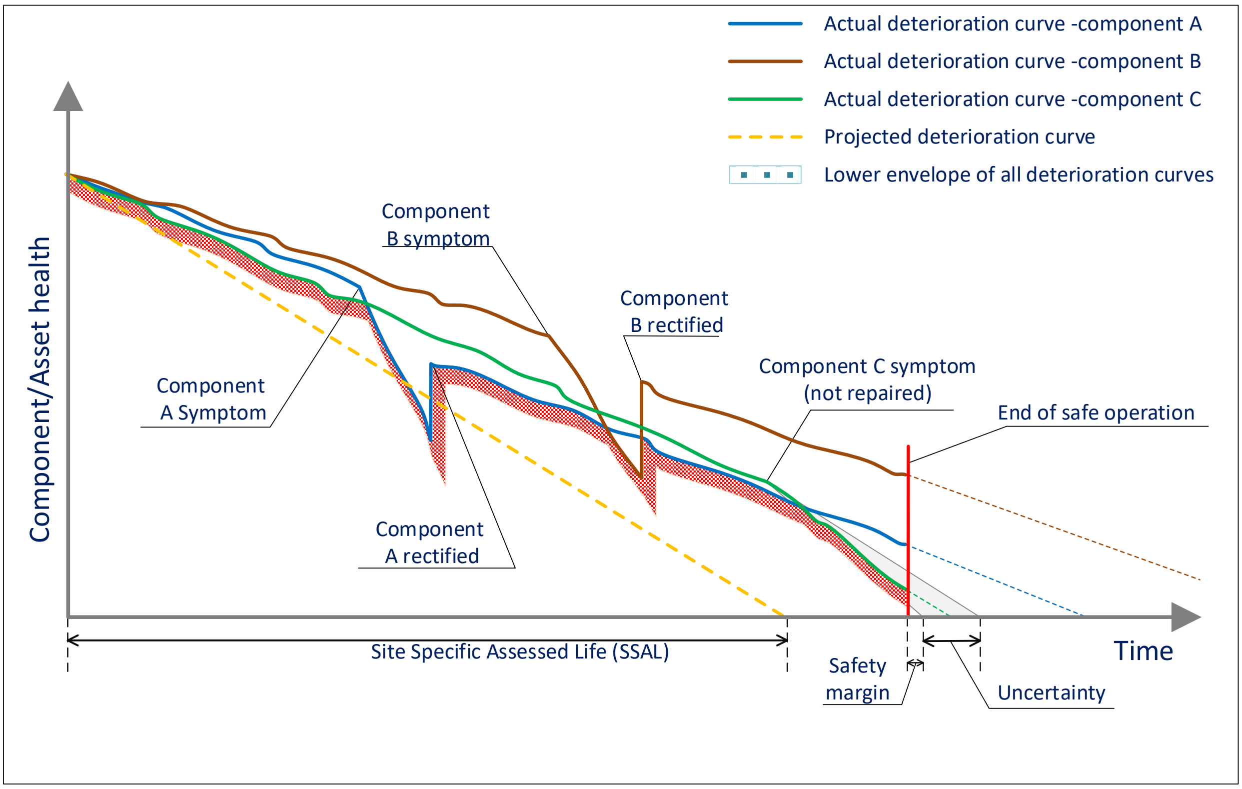


Figure 16: Single component with symptom

Case 3: Multiple components with symptoms (Figure 17)

In this case, three components in the critical load path are considered. Since the overall structure is no stronger than the weakest of the components, the resulting deterioration curve is the lower envelope of the deterioration curves for all three components. It can be seen in the figure how symptoms are detected for components A and B, but the problems are rectified as described in Case 2. However, a symptom is detected for component C sufficiently late in the life of the structure that it is decided not to replace or repair this component. The Site-Specific Expected Life for component C, taking into account the uncertainty and safety margin, determines the time where safe operation ends.

2894 

2895 **Figure 17: Multiple components with symptoms**

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