



BSI Standards Publication

Wind energy generation systems

Part 28: Through-life management and life extension of wind power assets

National foreword

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A list of organizations represented on this committee can be obtained on request to its committee manager.

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TECHNICAL SPECIFICATION

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

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

ICS 27.180

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

WIND ENERGY GENERATION SYSTEMS –

Part 28: Through-life management and life extension of wind power assets

FOREWORD

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IEC TS 61400-28 has been prepared by IEC technical committee 88: Wind energy generation systems. It is a Technical Specification.

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

Draft	Report on voting
88/955/DTS	88/1053/RVDTS

Full information on the voting for its approval can be found in the report on voting indicated in the above table.

The language used for the development of this Technical Specification is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/publications.

A list of all parts in the IEC 61400 series, published under the general title *Wind energy generation systems*, can be found on the IEC website.

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

- reconfirmed,
- withdrawn, or
- revised.

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 document 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 document has been published to enable wind farm operators to manage the production of electricity from wind turbines for the longest possible safe time, delaying 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 that the cumulative uncertainty, as defined in ISO/IEC guide 98-3 and estimated using methods defined in this document, including uncertainties in calculations, are used to estimate the variability of the results. It is described how this variability is to 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 document is implemented the better, but suitable procedures can 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 can 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 can 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 can be used by designers, manufacturers, developers, operators or third parties and can be used as part of due diligence. Application by stakeholders of practices and techniques specified in this document can 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 examples of situations:

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

These could 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 could 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 could also be made.

IEC 61400-1, IEC 61400-2, IEC 61400-3-1 and IEC 61400-3-2, 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 describes the 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:

- method for updating the lifetime (estimated prior to construction) for a specific site,
- which is being operated under specific site conditions and management procedures,
- which shows 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 lifetime 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 lifetime or beyond that stated in the type certificate, if available for the wind turbine. Turbines could prove to be safe and suitable to produce additional electricity, either during or beyond the site-specific lifetime. It is important to note that these are estimates of remaining lifetime, whether based on observations, measurements, statistical methods or simulations. The actual lifetime, with respect to the most significant mode of failure, can be longer or shorter.

It could 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 is 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 document may be used to define the technical inputs to any economic assessments, developed by stakeholders to value assets throughout their lifetime, but does not describe any particular economic models.

The focus of this document is on components in the primary load path and the safety system. For loading and structural integrity, accumulation of fatigue damage is described. 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 could contribute to the objectives of this document. It is left to the reader to extend the methods described in this document if relevant to topics relating to component reliability, with reference to IEC TS 61400-26-4.

WIND ENERGY GENERATION SYSTEMS –

Part 28: Through-life management and life extension of wind power assets

1 Scope

This part of IEC 61400, which is a 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. The document describes how to maintain those assets and collect suitable evidence to demonstrate to third parties that risks are minimised, particularly where risks are related to collateral damage or injury, such as could 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 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 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60300-3-11:2009, *Dependability management – Application guide – Reliability centred maintenance*

IEC 60812:2018, *Failure modes and effects analysis (FMEA and FMECA)*

IEC 61400-1:2019, *Wind energy generation systems – Part 1: Design requirements*

IEC 61400-2, *Wind turbines – Part 2: Small wind turbines*

IEC 61400-3-1:2019, *Wind energy generation systems – Part 3-1: Design requirements for fixed offshore wind turbines*

IEC 61400-3-2, *Wind energy generation systems – Part 3-2: Design requirements for floating offshore wind turbines*

IEC 61400-6, *Wind energy generation systems – Part 6: Tower and foundation design requirements*

IEC 61400-12-1, *Wind energy generation systems – Part 12-1: Power performance measurements of electricity producing wind turbines*

IEC 61400-12-2, *Wind energy generation systems – Part 12-2: Power performance measurements of electricity producing wind turbines based on nacelle anemometry*

IEC 61400-13, *Wind turbines – Part 13: Measurement of mechanical loads*

IEC 61400-25-1:2017, *Wind energy generation systems – Part 25-1: Communications for monitoring and control of wind power plants – Overall description of principles and models*

IEC 61400-25-2:2015, *Wind turbines – Part 25-2: Communications for monitoring and control of wind power plants – Information models*

IEC 61400-26-1, *Wind energy generation systems – Part 26-1: Availability for wind energy generation systems*

IEC TS 61400-26-4, *Wind energy generation systems – Part 26-4: Reliability of wind energy generation systems*

IEC 61511 (all parts), *Functional safety – Safety instrumented systems for the process industry sector*

ISO/IEC Guide 98-3 *Uncertainty of measurement – Part 3: Guide to the expression of uncertainty in measurement (GUM:1995)*

ISO 13381-1:2015, *Condition monitoring and diagnostics of machines – Prognostics – Part 1: General guidelines*

ISO 13822, *Bases of design for structures – Assessment of existing structures*

ISO 2394:2015, *General principles on reliability for structures*

EN 1990, *Basis of structural design*

WMO-TD No 1186, *Guidelines on Climate Data and Homogenization*

3 Terms, definitions and abbreviated terms

3.1 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

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

- IEC Electropedia: available at <https://www.electropedia.org/>
- ISO Online browsing platform: available at <https://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 1 to entry: The machine state deteriorates if Faults or Failures occur.

[SOURCE: ISO 13372:2012, 1.3]

3.1.3

design life

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, IEC 61400-2 or IEC 61400-3 series which was applicable at to time of the turbine design) is still ensured

Note 1 to entry: 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 and the IEC 61400-3-1:2019. 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.

Note 2 to entry: Several definitions of remaining life are used in this document and distinguished in Table 1.

3.1.4

detection

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 13372:2012, 1.7, modified – Notes have been deleted.]

3.1.6

fault

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

Note 1 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).

[SOURCE: ISO 13372:2012, 1.8, modified – Notes have been deleted, a Note to entry has been added.]

3.1.7

information

interpretation of measurements, for example, to provide status or evaluation of health (for example 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

LTE

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

Note 1 to entry: 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****NDT**

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

3.1.15**remaining useful life****RUL**

remaining time before system health falls below a defined failure threshold

Note 1 to entry: In this document, 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.

Note 2 to entry: See Table 1.

[SOURCE: ISO 13381-1:2015, 3.9, modified – Note 1 to entry has been added.]

3.1.16**site specific evaluation****SSE**

evaluation prior to wind farm construction of local site characteristics, the results of which to be used for evaluation of turbines and structures

Note 1 to entry: This document is restricted to describing the evaluation of turbine suitability for continued operation, rather than for the wind farm design, prior to construction.

3.1.17

site specific turbine suitability assessment

SSTSA

assessment of suitability of a wind turbine for a 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)

Note 1 to entry: The procedure followed by the reader of IEC TS 61400-28 shall align with the requirements of IEC 61400-1:2019, Clause 11 and Annex B for site-specific turbine suitability assessments.

Note 2 to entry: SSTSA is often undertaken as part of wind farm project certification, in accordance for example with IECRE OD 502:2018, Clause 6.3 (site suitability evaluation).

3.1.18

site specific assessed life

SSAL

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

Note 1 to entry: 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 could equally be designated as "prior to construction". Prior experience regarding reliability and modes of failure should be taken into account, if available.

Note 2 to entry: See Table 1.

3.1.19

site specific expected life

SSEL

at any moment during the operation, 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

Note 1 to entry: In general, the SSEL will depend on repairs, refurbishment and retrofits, including software updates.

Note 2 to entry: Examples of differences between an operating wind farm and one considered during planning as the base case include those observed with meteorological conditions, modifications of strategies relating to inspections or campaigns of measurements, modifications made to condition monitoring, specific observed defects or failures, together with corresponding RCAs / repairs / exchanges / upgrades, changes to operational strategy (including, for example, strategies regarding health monitoring, inspections, maintenance, service and electricity production) and substituted turbine components. SSEL is the total time passed since commissioning and the anticipated RUL. It could turn out to be greater or less than the design life or site-specific assessed life.

Note 3 to entry: See Table 1.

3.1.20

structural or major components

any component (including safety devices) of the turbine that carries a load 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

Note 1 to entry: 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
 - i) gearbox structures that react rotor torque,
 - ii) gearbox structures that react brake or high-speed rotor lock torque,
 - iii) shrink disc coupling connections,
- nacelle frame,
- yaw bearing and drive,
- tower,
- connections (of components listed above, for example bolted or welded connections),
- foundation,
- 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,
- Safety systems (refer to IEC 61511 series)
 - 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

SHM

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

[SOURCE: IEC 61400-6:2020, 9.5]

3.1.22

symptom

perception, made by means of human observations and measurements, which can indicate the presence of one or more faults

[SOURCE: ISO 13372:2012, 9.4]

3.1.23

tolerance

permitted deviation between the declared value of a quantity and the measured value

[SOURCE: IEC 60050-411:2007, 411-36-19]

3.1.24

through-life management

all activities relating to operation and management of the wind farm by the owner or designated agent

Note 1 to entry: 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

evaluation of loading during the design life of the wind turbine, for particular conditions which typically correspond to wind turbine type classes or those which relate to specific wind farms, in accordance with IEC 61400-1, its documentation and summary statement

Note 1 to entry: Older wind turbines, currently in operation could turn out not to 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 Abbreviated terms

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
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 document

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. The dark grey column indicates the transition from design evaluation to wind farm operation.								
(a)	Has the turbine or relevant component been categorized 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	x							
SSAL	x	x						
SSEL	x	x		x	x	x	x	x

The difference between the site-specific assessed life (SAAL) 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 how best to implement this document and to introduce best practices for management of wind power assets. These are to be applied throughout the operational life of the wind turbine asset and during a potential extended operational phase.

The objective of this document is to enable the integrity of the asset to be ensured 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 can 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 document 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:

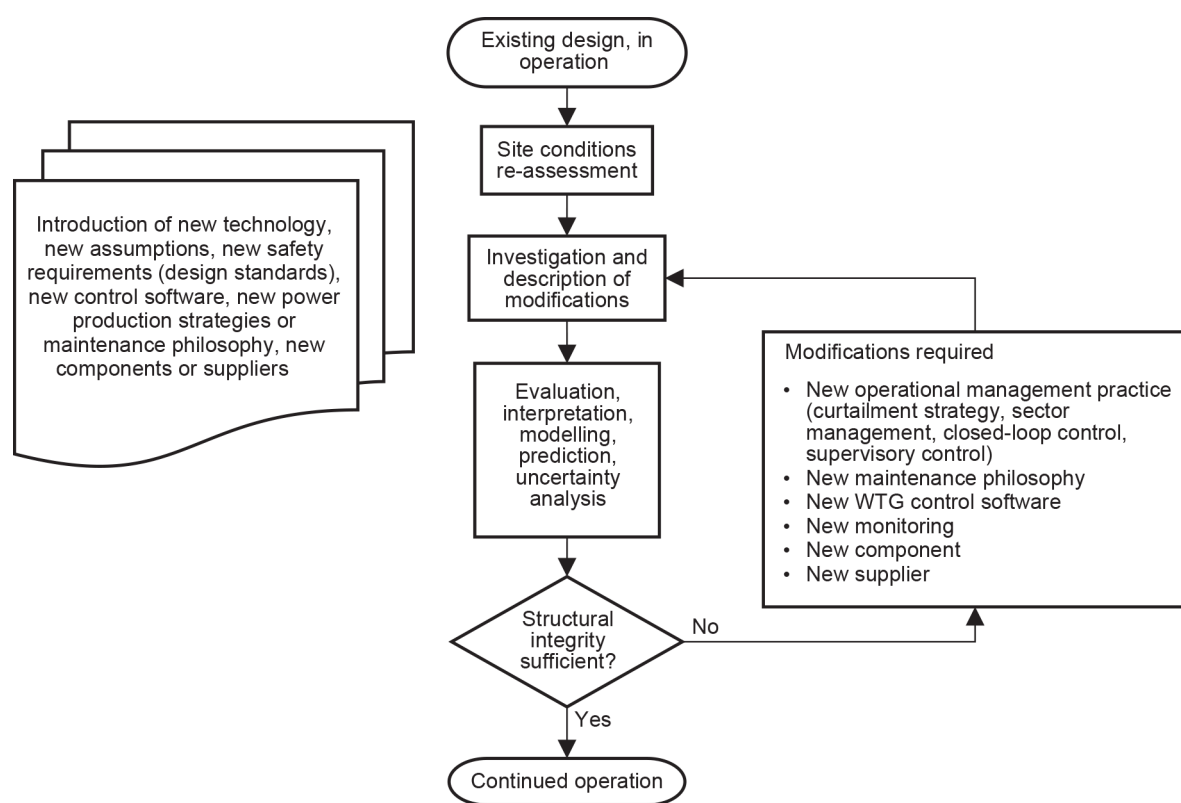
- different strategies regarding management of turbine operation,
- different levels of knowledge about the turbine,
- different levels of confidence in the methods selected,
- information used as inputs to the analysis.

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 document 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, assessment of the integrity of the primary structure shall comply with the principles described in ISO 2394:2015 (in particular Annex B). As indicated in ISO 13822, 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.



IEC

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 document (see Figure 2). These processes alone do not necessarily lead to an extension of the lifetime of the asset but can 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 document, since it has a direct bearing on the estimates made and the use to which they can 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.

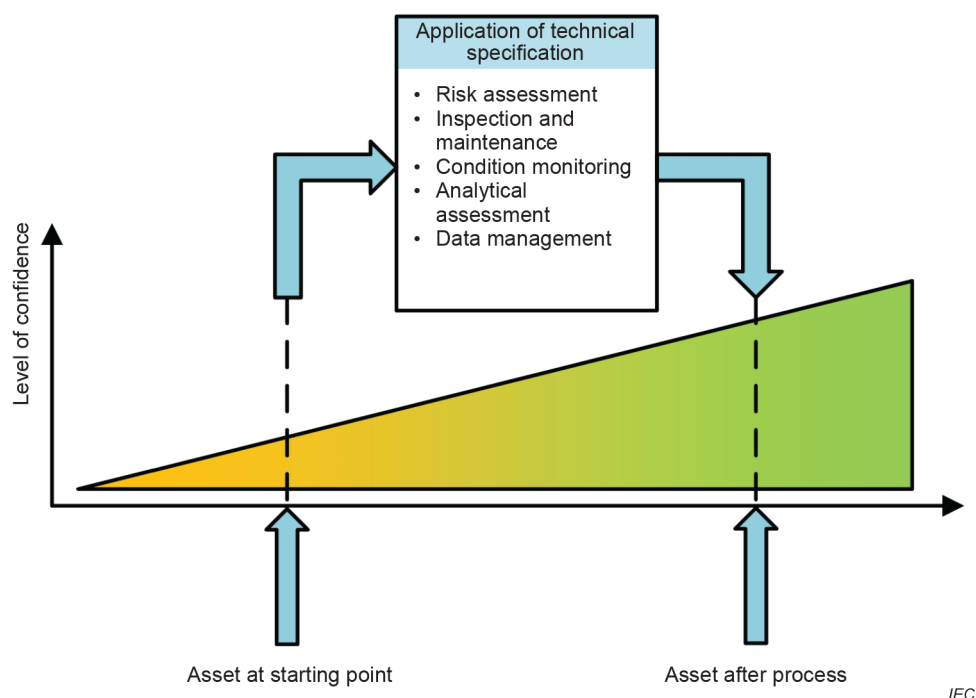
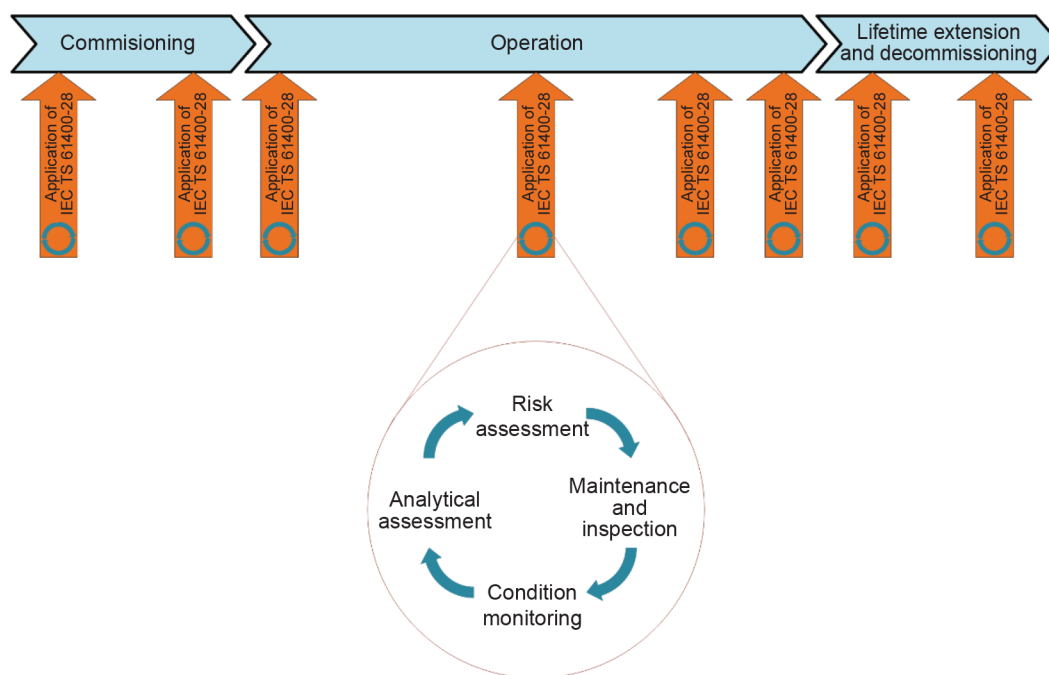


Figure 2 – Illustration of how the level of confidence can be improved by applying IEC TS 61400-28 (for example, relating to the estimated RUL)

Figure 3 shows three typical phases of operation of a wind turbine asset and illustrates how it is recommended to apply the methods described in this document repeatedly throughout the life. The guidance in this document can be applied at any time during asset lifetime. There are benefits from starting early and repeating the analyses described.

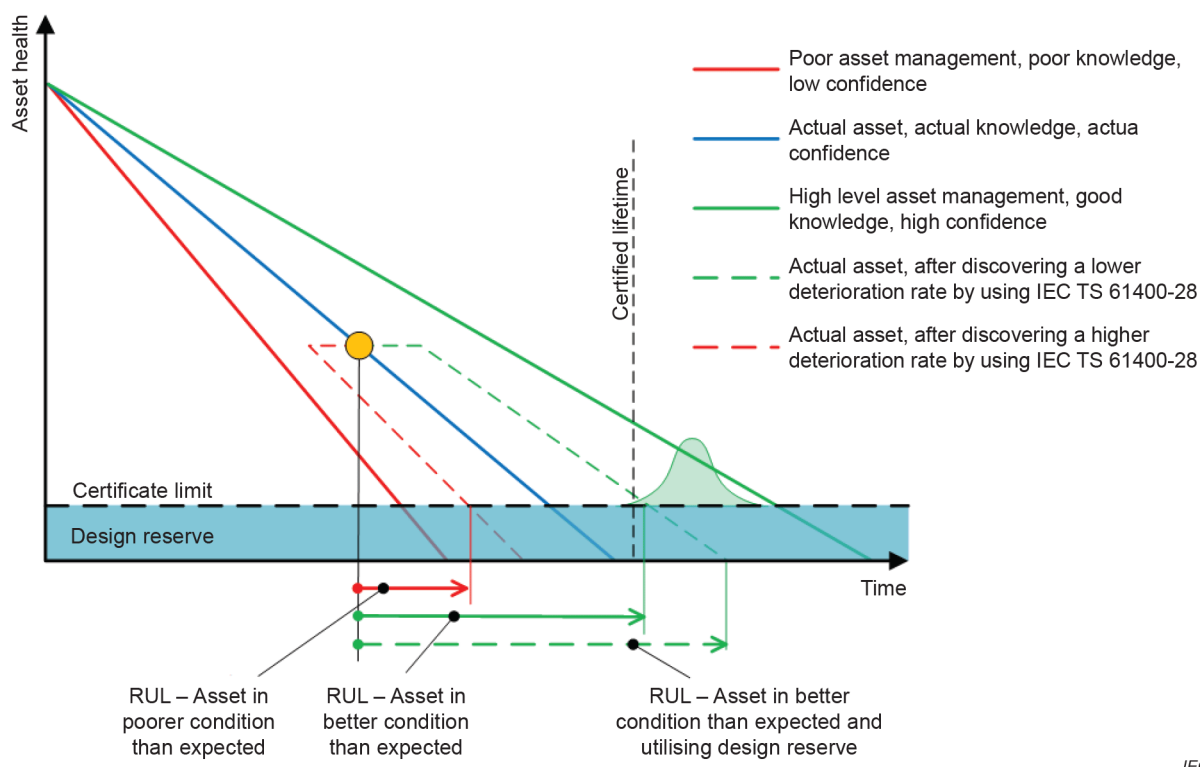


IEC

Figure 3 – The 3 typical phases of operation of a wind turbine

The consequences for the predicted RUL of implementing the methods described in this document 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 document (the yellow dot), methods are applied which lead to a more accurate estimate of the deterioration rate (dotted green curve or dotted red curve).



IEC

NOTE The constant gradient rate of deterioration over operating life shown in Figure 4 is an oversimplification: in reality the rate will vary over time in complex ways.

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 critical load path are in better condition than expected, at the time guidance in this document is applied, a new lower rate of deterioration (dotted green curve) can be justified, leading to an extended RUL. This can be because of the introduction of a new approach to maintenance or condition monitoring (providing improvement relative to the previous approach), or because the observed ambient site conditions are less severe than assumed (for example, turbulence intensity). It can 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 can have been present since the 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 document, 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 can 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 is no longer 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 should 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.

Further information is given in Annex G about the different strategies for management of wind power assets and the consequences for remaining useful life and extended operation.

4.2 Data management

Thorough approaches to data management are emphasised in this document. 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 document and specifically in Clause 5.

4.3 Reading guideline

This subclause aims to guide through some specific parts of the document. This is done via the illustration in Figure 5 of a typical asset management process. By implementing the processes described in this document, assets can be managed throughout the life more effectively and the potential for lifetime extension can 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).

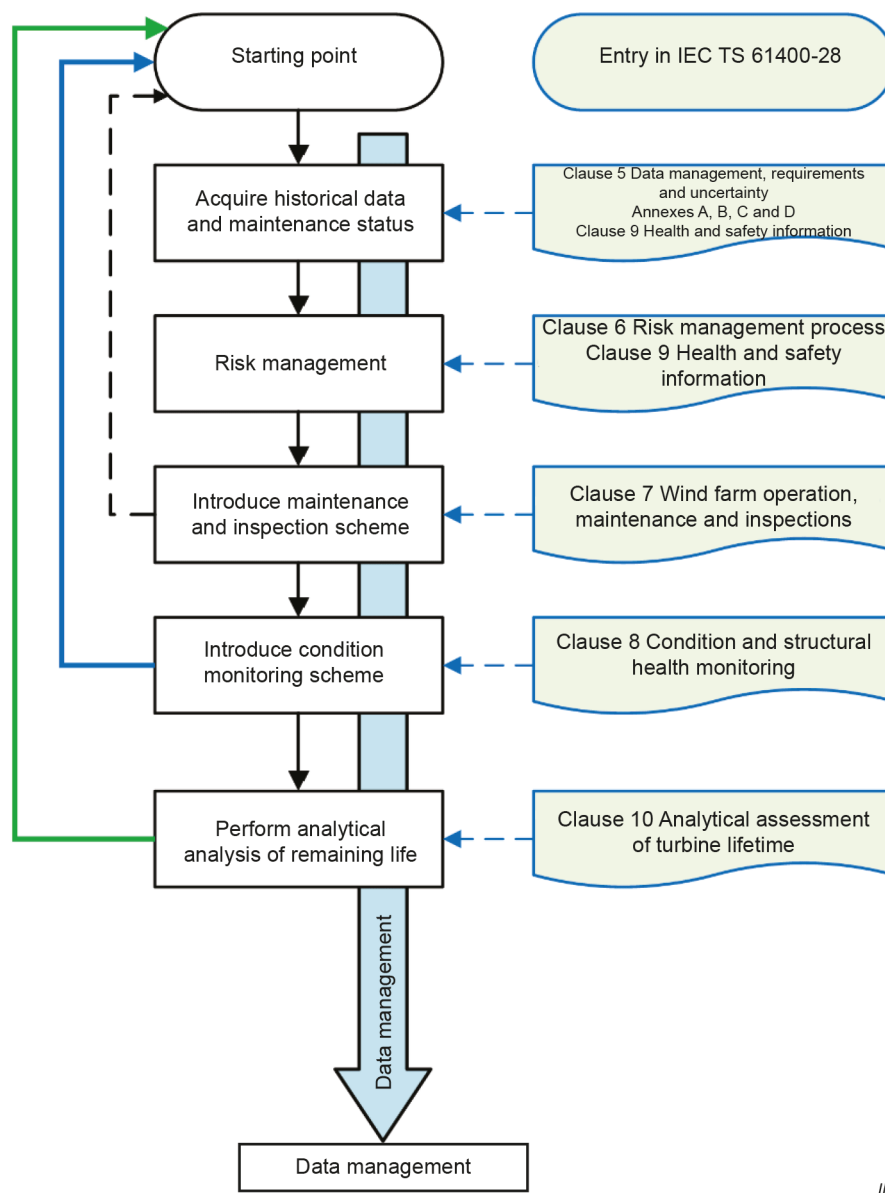


Figure 5 – Process of through-life management and lifetime extension – Data management is the backbone of the process

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 characterize 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 can 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 describes which information is important for assessing the loading history of components. Clause 5 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 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, it could be insufficient simply to continue with established or supplier-defined service instructions. Adoption of new measures shall be considered.

It should be assessed if failure consequences assumed prior to construction are still valid, or 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.

If no previous maintenance records exist, it is advisable to assume that service requirements and adequate equipment maintenance have not been implemented. Maintenance records shall 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 can still provide justification for extra measures beyond the service instructions. These can 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.

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. Often however these are categorised as inspection activities.

The condition monitoring can provide further input to the selected risk assessment methods, which in turn 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 document 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 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 can 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 are 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.

Probabilistic models, some derived from measured loads are described in Annex D. 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. Detailed requirements and methodologies for such assessments are outside the scope of this document.

Suggestions for methods of analytical RUL estimates can be found in Clause 10.

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.

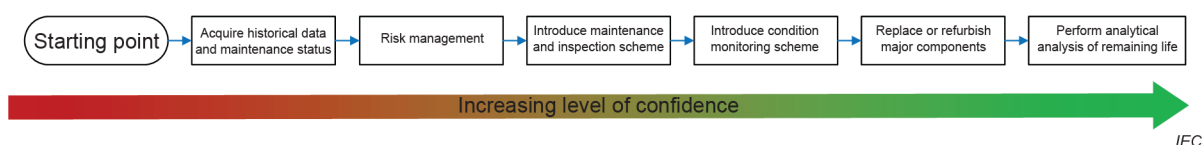


Figure 6 – Increase level of confidence, gradually by applying the methods

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 1 Clear guidance is provided in other documents such as the Reference Designation System for Power Plants (RDS-PP).

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 can be available from 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 2 There are benefits to filling gaps in measured operating data. Not all data are captured comprehensively during the lifetime of each individual turbine. Strategies exist to address the issue of regenerating missing data retrospectively, based on scrutiny of data from turbines of similar design, site conditions, maintenance history and operational philosophy. Implementing such strategies can enable missing data to be estimated, either relating to specific events or periods of time or to gain general insights gained regarding condition, reliability or optimum frequency of inspection or maintenance¹. This can be due for instance to wake interaction effects between turbines.

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 (as defined in IEC TS 61400-26-4). The process principally consists of the following elements, that are embodied, for example, in ISO 8000 series:

- validation and calibration,
- storage,
- protection,
- processing.

¹ Note that, for example owing to wake effects, turbines which are directly adjacent to each other can be subject to dissimilar fatigue loads and estimates of RUL.

Adoption of standards such as the ISO 8000 series facilitates portability and maximises the 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, IEC 61400-12-1, IEC 61400-12-2 and IEC 61400-12-13. Uncertainties should be estimated as a result of any data processing undertaken. As information which could be useful or interesting to the reader, calibration of instrumentation can typically be conducted by national calibration laboratories holding ISO/IEC 17025 accreditation (such as UKAS, NIST or other international equivalents).

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 [PPM²], 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 shall be assessed. For measured data, uncertainty shall be estimated according to ISO/IEC Guide 98-3 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 (allowable variations of thicknesses, diameters, rated power, weights, position of centre of gravity (CoG, inertia). Such tolerances can induce variance into the assessment by altering the strength or the dynamic loads.

NOTE Static data change over time, due for instance to maintenance activities, erosion, wear, material degradation or ingress of moisture. Changes include for example blade mass, blade mass moment imbalance, centre of mass, blade set angle.

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 thicknesses, tensile / fatigue strength, damping ratios, component mass and centres of mass. As such, they include data that can 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.

² PPM stands for "parts per million".

5.4 Data / information sources

5.4.1 Design information

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

- design codes and methods,
- wind turbine technical information, for instance building on that listed by typical conformity assessment schemes, with the following additions³:
 - 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.

³ The reader could be interested to use as a basis, the requirements and list of components within scope of wind turbine type certification, mandated in the IECRE-OD-501 series and also IEC 61400-1:2019, Clause 43.

5.4.2 Meteorological data

During wind farm development, a temporary or permanent meteorological mast can have been installed for site specific evaluation (SSE) 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 can have barometers, temperature and relative humidity sensors. Ground-based LiDAR, SoDAR or other equivalent equipment can 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) can be used in TLM and LTE assessments to compare design assumptions with actual site conditions.

It can be necessary to carry out additional measurements to support LTE assessments in the case of lack of 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 shall be made in accordance with IEC 61400-12-1⁴ and WMO-TD No 1186. Measurements can 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 shall 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 (for example, forward-facing LiDAR or spinner anemometers). To minimise the uncertainty associated with the data collected, methods defined in IEC 61400-12-2 may be applied. Averaging and gust data can be generated according to WMO-TD No 1186, 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 can be used to compare design assumptions with actual site conditions.

RUL assessment using measured data under actual site conditions shall be performed in accordance with the principles of principles of site-specific assessments defined in IEC 61400-1:2019, Clause 11.

⁴ The reader is encouraged to review the requirements of the accreditation scheme for the test house, for example ISO/IEC 17025.

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 can 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 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, IEC 61400-1 and IEC 61400-3-1 and WMO-TD No 1186).

Subclause 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 can be constructed to enable structural reserve margins to be calculated, using an absolute approach. The assumptions used prior to construction can be evaluated afresh, based on the new evidence available.

5.4.5 SCADA data

IEC 61400-25-1 and IEC 61400-25-2 define the parameters to be recorded by SCADA systems. However, few are mandatory and most are optional. IEC 61400-25-1:2017, Table 3 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 can be fewer than a hundred logged channels, whilst several hundred are typically logged in wind turbines designed more recently.