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TITLE: <b>Wind energy generation systems – Part 9: Probabilistic design measures for wind turbines</b>
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# INTERNATIONAL ELECTROTECHNICAL COMMISSION

## WIND ENERGY GENERATION SYSTEMS

### Part 9: Probabilistic design measures for wind turbines

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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.

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## INTRODUCTION

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# WIND ENERGY GENERATION SYSTEMS

## Part 9: Probabilistic design measures for wind turbines

### 1 Scope

This Technical Specification sets out minimum requirements to the use of probabilistic design measures in order to ensure the structural and mechanical integrity of wind turbines. The TS shall be based on the general approach in ISO 2394, which also forms the basis for IEC 61400-1. In 61400-1 the design verification approach is based on deterministic design using safety factors. However, edition 4 opens for introduction of probabilistic design in an informative annex specifying requirements to the calibration of structural material safety factors and structural design assisted by testing. This TS provides appropriate methodologies and requirements for full probabilistic design by taking into account specific uncertainties on not only material properties but also on environmental conditions, design models and the degree of validation.

### 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 61400-1, *Wind energy generation systems - Part 1: Design requirements*

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

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

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

IEC 61400-4, *Wind energy generation systems - Part 4: Design requirements for wind turbine gearboxes*

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

IEC 61400-8, *Wind energy generation systems - Part 8: Design of wind turbine structural components (CDV version)*

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

IEC 61400-13, *Wind energy generation systems – Part 13: Measurement of mechanical loads*

IEC TS 61400-31, *Wind energy generation systems – Part 31: Siting Risk Assessment (DTS version)*

IEC 61400-50-1, *Wind energy generation systems – Part 50-1: Wind measurement – Application of meteorological mast, nacelle and spinner mounted instruments*

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

### 50 **3 Terms and definitions**

#### 51 **3.1**

#### 52 **limit states**

53 state of a structure beyond which the structure no longer satisfies the design criteria

54 [SOURCE: ISO 2394]

#### 55 **3.2**

#### 56 **parked wind turbine**

57 turbine being either in a standstill or an idling condition, depending on the design of the wind  
58 turbine

59 [SOURCE: IEC 61400-1]

#### 60 **3.3**

#### 61 **reference wind speed**

62  $V_{ref}$

63 basic parameter for wind speed used for defining wind turbine classes

64 Note 1 to entry: Other design related climatic parameters are derived from the reference wind speed and other  
65 basic wind turbine class parameters (see Clause 6).

66 Note 2 to entry: A turbine designed for a wind turbine class with a reference wind speed  $V_{ref}$  is designed to  
67 withstand climates for which the extreme 10 min average wind speed with a return period of 50 years at turbine hub  
68 height is lower than or equal to  $V_{ref}$ .

69 [SOURCE: IEC 61400-1]

#### 70 **3.4**

#### 71 **site data**

72 environmental, seismic, soil and electrical network data for the wind turbine site

73 Note 1 to entry: Wind data shall be the statistics of 10 min samples unless otherwise stated.

74 [SOURCE: IEC 61400-1]

#### 75 **3.5**

#### 76 **standstill**

77 condition of a wind turbine that is stopped

78 [SOURCE: IEC 61400-1]

#### 79 **3.6**

#### 80 **support structure**

81 part of a wind turbine comprising the tower and foundation

82 [SOURCE: IEC 61400-1]

#### 83 **3.7**

#### 84 **turbulence intensity**

85  $I$

86 ratio of the wind speed standard deviation to the mean wind speed, determined from the same  
87 set of measured data samples of wind speed, and taken over a specified period of time

88 [SOURCE: IEC 61400-1]

89 **3.8**  
90 **wind turbine site**  
91 location of an individual wind turbine either alone or within a wind farm

92 [SOURCE: IEC 61400-1]

93 **3.9**  
94 **component class**  
95 classification of the wind turbine structural components according to redundancy and safety  
96 requirements

97 Note 1 to entry: Refer to IEC 61400-1.

98 [SOURCE: IEC 61400-6]

99 **3.10**  
100 **reliability class**  
101 class of structures or structural members for which a particular specified degree of reliability is  
102 required

103 **3.11**  
104 **design situations**  
105 sets of physical conditions representing the real conditions occurring during a certain time  
106 interval for which the design will demonstrate that relevant limit states are not exceeded

107 [SOURCE: IEC 61400-6]

108 **3.12**  
109 **effect of actions**  
110 effect of actions (or action effect) on structural members or on the whole structure

111 Note 1 to entry: Internal force, moment, stress and strain are examples of action effect on structural members.  
112 Deflection and rotation are examples of action effect on the whole structure.

113 [SOURCE: IEC 61400-6]

114 **3.13**  
115 **fatigue limit state**  
116 structural failure due to damage accumulation under effects of repeated loading

117 [SOURCE: IEC 61400-6]

118 **3.14**  
119 **serviceability limit state**  
120 state which corresponds to conditions beyond which specified service requirements for a  
121 structure or structural element are no longer met

122 [SOURCE: IEC 61400-6]

123 **3.15**  
124 **ultimate limit state**  
125 limit states which generally correspond to the maximum load bearing capacity

126 Note 1 to entry: This generally corresponds to the maximum load-carrying resistance of a structure or structural  
127 element but in some cases to a strain or deformation limit.

128 [SOURCE: IEC 61400-6]

129 **3.16**  
130 **reliability**  
131 ability of a structure or structural member to fulfil the specified requirements, during the working  
132 life, for which it has been designed.

133 Note 1 to entry: Reliability is often expressed in terms of probability.

134 Note 2 to entry: Reliability covers safety, serviceability, and durability of a structure.

135 [SOURCE: ISO 2394]

136 **3.17**  
137 **structural safety**  
138 ability (of a structure or structural member) to avoid exceedance of ultimate limit states,  
139 including the effects of specified accidental phenomena, with a specified level of reliability,  
140 during a specified period of time

141 [SOURCE: ISO 2394]

142 **3.18**  
143 **reliability-based design**  
144 design procedure that is subjected to prescribed reliability level of the structure

145 [SOURCE: ISO 2394]

146 **3.19**  
147 **member reliability**  
148 reliability of a single structural member which has one single dominating failure mode

149 [SOURCE: ISO 2394]

150 **3.20**  
151 **system reliability**  
152 reliability of a system of more than one relevant structural member or a structural member which  
153 has more than one relevant failure mode

154 [SOURCE: ISO 2394]

155 **3.21**  
156 **resistance**  
157 ability of a structure (or a part of it) to withstand actions without failure

158 [SOURCE: ISO 2394]

159 **3.22**  
160 **target reliability**  
161 specified average acceptable failure probability that is to be reached as close as possible

162 Note 1 to entry: Reliability targets are generally model dependent and need to be set for each case considered  
163 based on the models used.

164 [SOURCE: ISO 2394]

165 **3.23**

166 **reliability-based design**

167

168 A design procedure that is subjected to prescribed reliability level of the structure.

169 [SOURCE: ISO 2394]

170 **3.24**

171 **risk-informed design**

172 design optimized with due consideration of the total risks, including loss of lives and injuries,  
173 damages to the qualities of the environment, and monetary losses

174 Note 1 to entry: Risk-based design is presently not generally accepted by all national standards and codes.

175 [SOURCE: ISO 2394]

176 **3.25**

177 **robustness**

178 ability of a structure to withstand adverse and unforeseen events (like fire, explosion, impact)  
179 or consequences of human errors without being damaged to an extent disproportionate to the  
180 original cause

181 [SOURCE: ISO 2394]

182 **3.26**

183 **hazard**

184 unusual and severe threat, e.g. a possible abnormal action or environmental influence,  
185 insufficient strength or stiffness, or excessive detrimental deviation from intended dimensions

186 [SOURCE: ISO 2394]

187 **3.27**

188 **limit state**

189 state beyond which a structure no longer satisfies the design criteria

190 [SOURCE: ISO 2394]

191 **3.28**

192 **serviceability limit states**

193 limit state concerning the criteria governing the functionalities related to normal use

194 [SOURCE: ISO 2394]

195 **3.29**

196 **limit state function**

197 function  $g(X_1, X_2, \dots, X_n)$  of the basic variables, which characterizes a limit state when  
198  $g(X_1, X_2, \dots, X_n) = 0$

199 [SOURCE: ISO 2394]

200 **3.30**

201 **basic variables**

202 variables representing physical quantities which characterize actions and environmental  
203 influences, material and soil properties, and geometrical quantities

204 [SOURCE: ISO 2394]

205 **3.31**

206 **design service life**

207 assumed period for which a structure or a structural member is to be used for its intended  
208 purpose with anticipated maintenance, but without substantial repair being necessary

209 [SOURCE: ISO 2394]

210 **3.32**

211 **model uncertainty**

212 basic variable related to the accuracy of physical or statistical models

213 [SOURCE: ISO 2394]

214 **3.33**

215 **aleatory uncertainty**

216 inherent variability typically associated with the loading environment, the geometry of the  
217 structure, and the material properties

218 [SOURCE: ISO 2394]

219 **3.34**

220 **epistemic uncertainty**

221 lack of knowledge that, in principle, can be reduced by measurements or improved theories

222 Note 1 to entry: The exact borderline between aleatory and epistemic is not always unambiguous.

223 [SOURCE: ISO 2394]

224 **3.35**

225 **hierarchical modelling of uncertainty**

226 random variable is a function of other random variables

227 [SOURCE: ISO 2394]

228 **3.36**

229 **probabilistic methods**

230 verification methods in which the relevant basic variables are treated as random variables,  
231 random processes, and random fields, discrete or continuous

232 [SOURCE: ISO 2394]

233 **3.37**

234 **reliability index**

235  $\beta$

236 substitute for the failure probability  $\beta = \Phi^{-1}(P_f)$  where  $\Phi^{-1}$  is the inverse standardized normal  
237 distribution

238 [SOURCE: ISO 2394]

239 **3.38**

240 **structural model**

241 idealisation of the structure, physical, mathematical, or numerical, used for the purposes of  
242 analysis, design, and verification

243 [SOURCE: ISO 2394]

244 **3.39**

245 **First/Second Order Reliability Methods - FORM/SORM**

246 numerical methods used for determination of the reliability index  $\beta$

247 [SOURCE: ISO 2394]

248 **3.40**

249 **reference period**

250 period of time used as a basis for assessing the design value of variable and/or accidental  
251 actions

252 [SOURCE: ISO 2394]

253 **3.41**

254 **load effect**

255 effect of actions (loads) is a result of actions on a structural member (e.g. internal force,  
256 moment, stress, strain) or on the whole structure (e.g. deflection, rotation)

257 [SOURCE: based on ISO 2394]

258

259

260

261 **4 Symbols and abbreviations**

262 **4.1 Symbols and units**

263 **TO BE COMPLETED FOR THE FINAL VERSION OF THE TEXT**

$C$	scale parameter of the Weibull distribution function	[m/s]
$c$	environmental conditions	[-]
$D$	rotor diameter	[m]
$D_{adm}$	admissible damage level	[-]
$D(t)$	accumulated damage at time $t$	[-]
$E$	event	[m]
$I_{ref}$	reference value of the turbulence intensity corresponding to the 70 % quantile at 15 m/s	[-]
$I_{eff}$	effective turbulence intensity	[-]
$k$	shape parameter of the Weibull distribution function	[-]
$m$	Wöhler curve exponent	[-]
$n_i$	counted number of fatigue cycles in load bin $i$	[-]
$N(\cdot)$	number of cycles to failure as a function of the stress (or strain) indicated by the argument (i.e. the characteristic S-N curve)	[-]
$N$	return period for extreme situations	[years]

$p$	air pressure	[N/m <sup>2</sup> ]
$P(-)$	probability	[-]
$P_f$	probability of failure	[-]
$\Delta P_f$	annual probability of failure	[-]
$P_{f E}$	probability of failure conditional on event $E$	[-]
$P_{f E,v,c}$	probability of failure conditional on an event $E$ , mean wind speed $v$ and specific wind conditions $c$	[-]
$g(\cdot)$	limit state equation	[-]
$F_X(x)$	probability distribution function for a stochastic variable $X$	[-]
$f_X(x)$	probability density function for a stochastic variable $X$	[-]
$X$	stochastic variable	[-]
$K$	material parameter of the SN-curve	[-]
$\theta$	statistical parameters in probability distribution functions $F_X(x \theta)$	[-]
$Y$	stochastic variable in hierarchical stochastic model	[-]
$P_s$	survival probability	[-]
$S$	load effect	[-]
$L$	load effect	[-]
$N_{ref}$	reference number of cycles for the equivalent load	[-]
$L_E$	is the extreme load effect during event $E$	[-]
$R$	resistance	[-]
$R$	stress ratio	[-]
$T_L$	design lifetime	[y]
$v$	mean wind speed	[-]
$s_i$	the stress (or strain) level associated with the counted number of cycles in bin $i$	[-]
$T$	gust characteristic time	[s]
$t$	time	[s]
$V$	wind speed	[m/s]
$V(z)$	wind speed at height $z$	[m/s]
$V_{ave}$	annual average wind speed at hub height	[m/s]
$V_{cg}$	extreme coherent gust magnitude over the whole rotor swept area	[m/s]
$V_{eN}$	expected extreme wind speed (averaged over three seconds), with a recurrence time interval of $N$ years. $V_{e1}$ and $V_{e50}$ for 1 year and 50 years, respectively	[m/s]
$V_{gust}$	largest gust magnitude with an expected return period of 50 years	[m/s]
$V_{hub}$	wind speed at hub height	[m/s]
$V_{in}$	cut-in wind speed	[m/s]
$V_{50}$	extreme wind speed (averaged over 10 minutes) with a recurrence interval of 50 years	[m/s]

$V_{100}$	extreme wind speed (averaged over 10 minutes) with a recurrence interval of 100 years	[m/s]
$V_{out}$	cut-out wind speed	[m/s]
$V_r$	rated wind speed	[m/s]
$V_{ref}$	reference wind speed	[m/s]
$V_{ref,T}$	reference wind speed for tropical-like conditions	[m/s]
$V(y,z,t)$	longitudinal wind velocity component to describe transient horizontal wind shear	[m/s]
$X_M$	random variable representing a model uncertainty for $M$	[-]
$W_X$	random variable representing an environmental parameter $X$	[-]
$x, y, z$	co-ordinate system used for the wind field description; along wind (longitudinal), across wind (lateral) and height respectively	[m]
$z_{hub}$	hub height of the wind turbine	[m]
$z_r$	reference height above ground	[m]
$z_0$	roughness length for the logarithmic wind profile	[m]
$\alpha$	wind shear power law exponent	[-]
$\beta$	parameter for extreme direction change model	[-]
$\beta$	Reliability index	[-]
$\gamma_f$	partial safety factor for loads	[-]
$\Delta$	Uncertainty on the Palmgren-Miner damage summation model	[-]
$\gamma_M, \gamma_R$	partial safety factor for resistances	[-]
$\lambda_F$	annual failure rate	
$\lambda_E$	rate of events	
$\theta(t)$	wind direction change transient	[deg]
$\theta_{cg}$	angle of maximum deviation from the direction of the average wind speed under gust conditions	[deg]
$\theta_{eN}$	extreme direction change with a return period of $N$ years	[deg]
$\Lambda_1$	turbulence scale parameter defined as the wavelength where the non-dimensional, longitudinal power spectral density, $fS_1(f)/\sigma_1^2$ , is equal to 0,05	[m]
$\rho$	air density	[kg/m <sup>3</sup> ]
$\sigma_1$	hub-height longitudinal wind velocity standard deviation	[m/s]
$\Phi$	standardized normal probability distribution function	[-]
$\varphi$	standardized normal probability density function	[-]
$\sigma_{lim}$	Component capacity (e.g. yield strength, tensile strength) in terms of limiting stress level	MPa
$\sigma_m$	Mean stress	MPa
$\sigma_R$	stress range	MPa
$S_u$	ultimate limit strength	MPa

$\sigma_Y$  yield strength of the material MPa

264 **4.2 Abbreviated terms**

265	COV	coefficient of variation
266	DLC	design load case
267	ECD	extreme coherent gust with direction change
268	EDC	extreme wind direction change
269	EOG	extreme operating gust
270	ETM	extreme turbulence model
271	EWM	extreme wind speed model
272	EWS	extreme wind shear
273	FMEA	failure mode and effect analysis
274	FORM	First Order reliability Method
275	FRT	fault ride through
276	IFORM	Inverse First-Order Reliability Method
277	SORM	Second Order reliability Method
278	NWP	normal wind profile model
279	NTM	normal turbulence model
280	ULS	ultimate limit state
281	FEM	Finite Element Method
282	LSE	Limit State Equation
283	LVRT	Low Voltage Ride Through
284	PSF	Partial Safety Factor
285	RNA	Rotor Nacelle Assembly
286	S-N	Stress- Cycle Curve for fatigue of materials
287	PSHA	probabilistic seismic hazard analyses

288  
289

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290 **5 Principal elements**

291 **5.1 General**

292 The following clauses specify essential requirements to the use of probabilistic design  
 293 measures in order to ensure the structural and mechanical integrity of wind turbines. The  
 294 specification of requirements applies to the design, siting and reassessment of a wind turbine  
 295 system and its components, accounting for validated influences of the manufacturing,  
 296 operations, and maintenance, and site-specific environmental conditions.

297 This document provides appropriate methodologies, probabilistic models, and requirements for  
 298 probabilistic assessment of components in line with IEC61400-1. Probabilistic assessment is  
 299 an alternative to the semi-probabilistic (deterministic) assessment procedures given in IEC  
 300 61400-1. The reliability assessment is performed for individual components and failure modes,  
 301 and the resulting system reliability is implicitly accepted. The designer may select components  
 302 and failure modes for probabilistic assessment, while the remaining failure modes shall be  
 303 verified using traditional semi-probabilistic methods. It is allowed to do a full probabilistic  
 304 analysis, or use probabilistic methods to calibrate specific partial safety factors for use in semi-  
 305 probabilistic assessment. Specific partial safety factors for a subset of limit states should be  
 306 calibrated such that the average reliability over the subset is as close to the target reliability as  
 307 possible. In IEC 61400-1, the same partial safety factors are applied for a range of load cases,  
 308 components, and environmental conditions, and as a result the obtained reliability level may  
 309 deviate from the target reliability specified in this document. Deviations from the methodologies,  
 310 probabilistic models, and requirements are allowed if properly justified.

311 The main steps in a reliability assessment for a selected component and failure mode are the  
 312 following:

- 313 a) Determine appropriate consequence class and target annual reliability index (see 5.2)
- 314 b) Model specification
  - 315 i) Formulate limit state equations (see 7)
  - 316 ii) Develop appropriate probabilistic models for the variables in the limit state equations  
 317 (see 6 and additionally 9 for siting)
- 318 c) Reliability analysis
  - 319 i) Perform a reliability analysis and compute the annual reliability index (see 8)
  - 320 ii) Assess the accuracy of the computation and perform sensitivity studies (see 8)
- 321 d) Assessment
  - 322 i) For design situations: Perform a design optimization loop over steps b)-c) until a  
 323 design is found where the target reliability is reached or exceeded in all years of the  
 324 planned lifetime.
  - 325 ii) For siting: The component has sufficient reliability on a site if the target reliability is  
 326 reached or exceeded in all years of the planned lifetime.
  - 327 iii) For reassessment: The component has sufficient reliability for continued operation  
 328 for as many years as the target reliability is reached or exceeded.

329 The reliability model and assessment procedure should undergo verification by comparing the  
 330 results of the reliability analysis with the result of a deterministic analysis for a baseline model.

331

## 332 5.2 Target Reliability Level and Component Classes

333 In Table 1 target reliability levels are given dependent on the consequence of failure (component class)<sup>1</sup>  
 334 for ultimate limit states. The target reliability level may be achieved through a combination of design,  
 335 prescribed scheduled maintenance and parts replacement, and health monitoring. For fatigue limit  
 336 states, the target is given for the annual reliability index in the last year of the design lifetime. For limit  
 337 states related to the ultimate strength, the target is given for the year with the largest annual failure  
 338 probability, typically the first year of operation. Exceptions to these target reliabilities should be permitted  
 339 if justified based on ISO 2394<sup>2</sup>. Reliability targets for serviceability limit states should be defined based  
 340 on their consequences, see ISO 2394 and JCSS PMC. Target reliabilities for special safety class wind  
 341 turbines should be agreed between the manufacturer, customer and relevant authorities.

342 **Table 1 – Target reliability levels.**

Component class	Annual target probability of failure	Annual target reliability index
Component class 1	$2 \cdot 10^{-3}$	2.9
Component class 2	$5 \cdot 10^{-4}$	3.3
Component class 3	$5 \cdot 10^{-5}$	3.9

## 343 5.3 Limit States

344 For the failure modes selected for probabilistic assessment, limit state equations should be  
 345 formulated based on the deterministic design equation, representing variables by their  
 346 probability distributions, instead of using characteristic values and partial safety factors.  
 347 Uncertainties related to external conditions, load assessment, and resistance (as described  
 348 further in chapter 6) should be included either directly (e.g. the input variable is represented  
 349 directly as a random variable in the limit state equation) or indirectly (e.g. the effect of  
 350 uncertainty on one or more variables is represented as a model uncertainty multiplied on the  
 351 load effect) in the limit state equation.

352 Reliability assessments may be performed for ultimate and serviceability limit states such as:

- 353 – Exceedance of the ultimate strength
- 354 – Fatigue failure
- 355 – Static Instability
- 356 – Dynamic Instability
- 357 – Component interference due to deformation
- 358 – Extreme vibrations
- 359 – Loss of control functionality
- 360 – Permanent deformations

## 361 5.4 Data Validity

362 Probabilistic models for physical quantities should be based on representative data, and model  
 363 uncertainties should be assessed to the degree possible through a combination of tests and  
 364 measurements such as:

- 365 – Material tests
- 366 – Test of sub-components / scaled components

<sup>1</sup> If human health and/or environment is at risk, a site-specific risk assessment with failure modes of tower collapse and throwing parts is to be performed, as defined in IEC TS 61400-31.

<sup>2</sup> Changes to the target reliability for specific cases can be motivated by e.g. the consequence of failure, cost of safety measure, or the level of uncertainties.

- 367 – Full-scale component tests
  - 368 – Load measurement campaigns (e.g. prototype testing)
  - 369 – Environmental data (e.g. met-mast data)
  - 370 – Operational data
- 371 The availability of data depends on whether the reliability assessment is made in relation to  
372 design, siting, or reassessment. Examples of typical situations and available data are:
- 373 – Design of RNA components for an IEC class or class S turbine (tests on material and sub-  
374 components, data from other wind turbine models)
  - 375 – Site-specific design of tower, sub-structure and/or foundations, or site assessment of an  
376 IEC class or class S turbine for a specific site (tests on material and components, load  
377 measurement campaigns, environmental data)
  - 378 – Re-assessment of a wind turbine during or near the end of the operational phase (tests on  
379 material and components, load measurement campaigns, environmental data, operational  
380 data, condition  
381 – monitoring data)
  - 382 – The possible influence of the following sources of uncertainty should be included in the  
383 analysis where relevant: Deviation in raw material quality
  - 384 – Nonconformity of finished parts to quality control specifications
  - 385 – Unknown part defects outside the scope of QC specifications (i.e., incomplete CTQ  
386 specifications due to incomplete knowledge)
  - 387 – Nonconformity of installation procedures to specifications
  - 388 – Site environmental conditions
  - 389 – Variability in operational practices, including controller issues
  - 390 – Variability in maintenance practices
  - 391 – Nonconformity of component repairs with specifications or standard industry practice.
- 392  
393

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## 394 6 Uncertainty representation and modelling

### 395 6.1 General

396 The uncertainties associated with the external conditions, load assessment, structural  
397 resistance and electrical / mechanical component reliability related to wind turbine control or  
398 safety system should be modelled for the wind turbine lifetime as part of a reliability analysis.

#### 399 6.1.1 Types of uncertainty

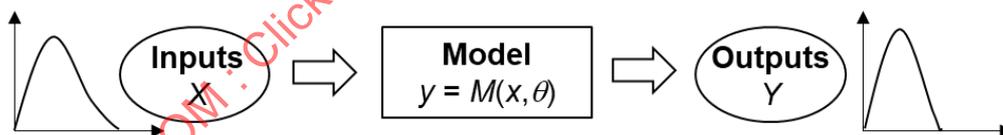
400 Various sources of uncertainty as for example natural / physical variability, statistical  
401 uncertainties, measurement uncertainties and model uncertainties exist.

402 The natural / physical uncertainties are typically uncertainties related to the external conditions,  
403 the geometry of the structure and the material properties and are often referred to as aleatory  
404 uncertainties.

405 The statistical uncertainties originate from limited information and data about external  
406 conditions, material properties, load validation etc. and are often referred to as epistemic  
407 uncertainties.

408 The measurement uncertainties originate from uncertainty in measurement setup, equipment,  
409 calibration or analysis of tests and are often referred to as epistemic uncertainties. The list of  
410 contributions to measurements uncertainty should be as complete as reasonable for the  
411 application and reflect the information available about accuracy.

412 The model uncertainties originate from idealizations and imperfections associated with  
413 describing a physical phenomenon using mathematical models. This includes the formulation  
414 of the models ( $M$ ), that attempt to represent the real world ( $Y$ ) based on a given input ( $X$ ), as  
415 well as the parameters ( $\theta$ ) of the model that are subject to uncertainty, see Figure 1. Model  
416 uncertainty is e.g. associated with aeroelastic models, finite element models, reduced-order  
417 representations, simplifications in failure criteria definitions and are often referred to as  
418 epistemic uncertainties.



419

420 **Figure 1 – Application of a mathematical model to estimate an output based on a given**  
421 **input.**

422 Uncertainties can be aleatory or epistemic and can change nature in different phases of the  
423 lifetime of a wind turbine. For example, a material property can be considered as aleatory before  
424 the manufacturing of a wind turbine, once the wind turbine is manufactured, it can be considered  
425 as an epistemic uncertainty.

#### 426 6.1.2 Interpretation of probability and treatment of uncertainty

427 In structural reliability analysis, the Bayesian interpretation of probability should be considered  
428 as the most adequate basis for the consistent representation of uncertainties, independent of  
429 their sources. It facilitates the joint consideration of analytically assessed uncertainties,  
430 evidence as obtained through observations and subjectively assessed uncertainties (expert  
431 knowledge).

432 Subjective information can e.g. be used to quantify the expected variation for a very limited test  
 433 sample based on previous test samples or to quantify physical or model uncertainties which  
 434 either cannot or are not practically possible to measure. However, subjectively assessed  
 435 uncertainties should be used with caution and the information used should be documented and  
 436 preferable obtained through a structured process as e.g. Cooke (1991).

437 In Bayesian probability theory, the values for probabilities are estimated based on an adequate  
 438 combination of data, theoretical arguments, and judgment. There is no distinction in the  
 439 treatment between aleatory and epistemic uncertainty. If large amounts of data are available,  
 440 the Bayesian interpretation coincides with the frequentist one.

441 Considering the probabilistic modelling of a random basic variable  $X$ , the principle in Bayesian  
 442 probability analysis is to model one or more of the parameters  $\theta$  (e.g. the mean and standard  
 443 deviation) of the probabilistic model (e.g. the probability distribution function) as random  
 444 variables themselves. The frequentist or subjective information available about  $X$  can then be  
 445 used in the probabilistic modelling of  $\theta$ .

446 All uncertainties that are of importance for the reliability analysis of a wind turbine or parts  
 447 thereof should be considered in the analysis using the theory of probability. A systematic  
 448 approach based on a hierarchy of uncertainties can support the identification of contributions  
 449 to uncertainty.

450 **6.1.3 Probabilistic model**

451 Depending on the nature of the reliability problem, basic variables can be represented as  
 452 random variables, random processes and random fields, discrete as well as continuous.

453 The probabilistic models should describe the uncertainties of individual random basic variables,  
 454 but also accommodate the consideration of the dependencies among them.

455 Dependencies often arise due to causality, spatial and/or temporal correlations and/or ergodic  
 456 states of underlying phenomena, as well as statistical and/or model uncertainties that commonly  
 457 affect the uncertainties of the individual variables.

458 The uncertainty in the basic variables and the dependencies among them can normally be  
 459 modelled by probability distribution functions  $f_X(X|\theta)$  and correlation coefficients  $\rho$  focussing on  
 460 the application of interest (e.g. extreme values).

461 A dependent or hierarchical modelling is recommended, where applicable. The dependent or  
 462 hierarchical model assumes that a random quantity  $Y$  can be written as a function of several  
 463 variables, each one representing a specific type of variability:

$$Y_{ijk} = f(X_i, X_{ij}, X_{ijk}) \tag{1}$$

464 The variables  $X_i, X_{ij}, X_{ijk}$  represent various origins, time scales of fluctuation, or spatial scales  
 465 of fluctuation. This modelling approach is for example relevant for the wind conditions, where  
 466 the wind speed standard deviation  $\sigma_1$  (turbulence) is dependent on e.g. the 10min mean wind  
 467 speed  $V_{hub}$  and terrain roughness.

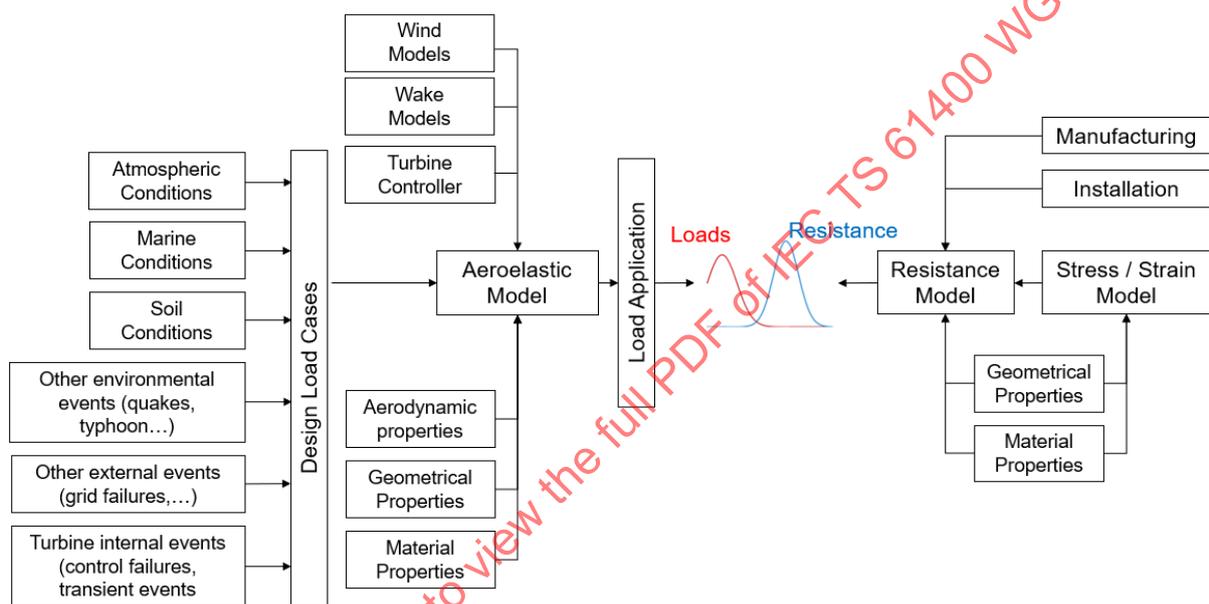
468 The probabilistic models should when relevant also accommodate the updating of the models  
 469 by additional information, which can become available with, for example, experiments, tests,  
 470 inspections, and monitoring. The Bayesian updating formula provides the operational basis for  
 471 this.

472 The description of uncertain quantities by probabilistic models should correspond to well-  
 473 defined outcome spaces (or populations) and the results of the reliability analysis are only valid  
 474 for the same sets.

475 The probabilistic models can be determined based on information from different e.g. wind  
 476 turbine types, design concepts or site conditions. In these cases, it should be justified that the  
 477 probabilistic model is representative and potential residual uncertainty should be covered by  
 478 model uncertainty.

#### 479 6.1.4 Uncertainties for wind turbines

480 The typical flow chart and uncertainties which should be considered in probabilistic design for  
 481 wind turbines are shown in Figure 2 and the principles for assessment of the individual  
 482 uncertainties are described in the following sub-sections.



483

484 **Figure 2 – Typical flow chart and uncertainties to be considered in probabilistic design**  
 485 **of wind turbine components.**

486 The *design load cases* defined in IEC 61400-1, IEC 61400-3-1 and IEC 61400-3-2 specify the  
 487 minimum number of design situations which should be considered. The uncertain input to the  
 488 design load cases is listed in the following:

- 489 • *Atmospheric conditions* represent the uncertainty in e.g. mean wind speed, extreme  
 490 wind speed (incl. tropical cyclones), turbulence, wind shear, air density and gust events.
- 491 • *Marine conditions* represent the uncertainty in e.g. wave conditions, current, tides and  
 492 storm surge.
- 493 • *Other environmental events* represent the uncertainty in e.g. temperature, lightning, ice  
 494 conditions and earthquakes.
- 495 • *Other external events* represent the uncertainty in e.g. grid fault, loss of electrical  
 496 network, low voltage ride through.
- 497 • *Turbine internal events* represent the uncertainty in e.g. controller failures (primary and  
 498 secondary layer protection functions), overspeed, actuators and braking systems.

499 The *aeroelastic model* is normally relying on a number of sub-models:

- 500 • *Wind models* represent the uncertainty in e.g. the Mann or Kaimal turbulence models.
- 501 • *Wake models* represent the uncertainty in e.g. the added wake turbulence method or  
502 dynamic wake meandering model.
- 503 • *Turbine controller* represents the uncertainty in e.g. a simplified controller  
504 implementation.

505 Additionally, the *aeroelastic model* is based on some input parameters which normally are  
506 constant for the different design load cases:

- 507 • *Aerodynamic properties* represent the uncertainty in e.g. lift and drag coefficients.
- 508 • *Geometrical properties* represent the uncertainty in e.g. thickness and length.
- 509 • *Soil / Material properties* represent the uncertainty in e.g. stiffness.

510 The aero-elastic simulations are normally post-processed in order to determine the input to the  
511 resistance model:

- 512 • *Load application* represent the uncertainty in e.g. extrapolation, contemporaneous  
513 loads, rainflow cycle counting and Miner's rule.

514 The *resistance model* or failure criteria is based on the following input parameters:

- 515 • *Manufacturing* represents the uncertainty in e.g. the manufacturing quality.
- 516 • *Installation* represents the uncertainty in e.g. the installation process and quality.
- 517 • *Geometrical properties* represent the uncertainty in e.g. thickness and length.
- 518 • *Material properties* represent the uncertainty in e.g. stiffness and strength.

519 Additionally, the resistance model is often dependent on a sub-model

- 520 • *Stress / Strain model* represent the uncertainty in stress and strain assessment for a  
521 load application e.g. through a finite-element model.

522 The individual physical, model, measurement and statistical uncertainties can be quantified  
523 directly and propagated through the flow chart in order to determine the resulting uncertainty in  
524 the load or resistance. Alternatively, the resulting uncertainty on load or resistance can be  
525 determined directly by other means.

## 526 **6.2 External condition uncertainty modelling**

### 527 **6.2.1 General**

528 The external conditions refer to the environmental and electrical conditions which affect the  
529 wind turbine or parts thereof. Environmental conditions can in general be separated into wind,  
530 marine, soil and other conditions.

531 The individual environmental conditions should be modelled by stochastic models established  
532 based on the standard conditions used for IEC class verification as defined in IEC 61400-1, IEC  
533 61400-3-1 and IEC 61400-3-2 or representative measurements for the quantity and application  
534 of interest. The term “representative” should be considered in relationship to the measurements  
535 available and expert knowledge used for defining the standard conditions used for IEC class  
536 verification.

537 The standard conditions cover along with the design load cases in IEC 61400-1, IEC 61400-3-  
538 1 and IEC 61400-3-2 the relevant design situations for a wind turbine for which stochastic  
539 models may be established.

540 Uncertainty representation and modelling for site specific conditions are described in chapter  
541 9.

## 542 **6.2.2 Wind conditions**

543 The atmospheric conditions can in general be separated into the standard wind conditions and  
544 other conditions defined in IEC 61400-1. The standard wind conditions are generally  
545 established by determining a characteristic value (typically 50 year value) for a single wind  
546 parameter or wind event e.g. turbulence or gust. The potential interaction of the individual wind  
547 conditions and non-linear interaction of the wind turbine controller can influence the wind turbine  
548 response and should if relevant be considered when the stochastic models are established.

549 Probabilistic models established for IEC class type certification (I-III & A+-C) should be based  
550 on the probabilistic models defined in IEC 61400-1 when available. Other wind conditions may  
551 be modelled by probabilistic models when these are in alignment with the general design  
552 philosophy in IEC 61400-1. As an example, the air density can be modelled by a probabilistic  
553 model with mean value equal to  $1.225 \text{ kg/m}^3$  as specified in IEC 61400-1 and other parameters  
554 determined based on a few reference sites. Probabilistic models established for IEC class “S”  
555 should be specified by the designer.

556 Alternatively, probabilistic models may be established based on representative wind or turbine  
557 measurements from a few reference sites. The probabilistic models may be developed by  
558 identifying the standard wind conditions (e.g. gusts or wind direction changes) from IEC 61400

559 -1 in wind or turbine measurements with a sufficient resolution to cover the spatial and time  
560 fluctuations. The probabilistic models should beyond the physical uncertainty in the wind  
561 conditions also represent the measurement and statistical uncertainty in the wind  
562 measurements used to establish them.

563 The turbulence model describes the spatial and time variation in the wind velocity field  
564 established through longitudinal, lateral and upward vector components, generally consistent  
565 with a specified 10-min average wind speed at hub height and reference turbulence intensity,  
566 see IEC 61400-1 Annex C. The model and statistical uncertainty related to the turbulence model  
567 should be quantified e.g. as part of the load uncertainty modelling, see section 6.3.

### 568 **6.2.2.1 Normal wind conditions**

569 The normal wind conditions are represented by the mean wind speed distribution, the Normal  
570 Wind Profile (NWP) and the Normal Turbulence Model (NTM) in IEC 61400-1.

571 The mean wind speed distribution  $F_{V_{hub}}(V_{hub})$  for the wind speed at hub height  $V_{hub}$  (10min  
572 reference period) is according to IEC 61400-1 defined as a Rayleigh distribution for the different  
573 IEC classes.

$$F_{V_{hub}}(V_{hub}) = 1 - \exp \left[ -\pi \left( \frac{V_{hub}}{2 V_{ave}} \right)^2 \right] \quad (2)$$

574 where  $V_{ave}$  is the annual average wind speed. The Rayleigh distribution is a special case of the  
 575 more general Weibull distribution which normally is used to characterize the mean wind speed  
 576 distribution in probabilistic models.

$$F_{V_{hub}}(V_{hub}) = 1 - \exp \left[ - \left( \frac{V_{hub}}{A} \right)^k \right] \quad (3)$$

577 where  $A$  and  $k$  are the scale and shape parameter. The NWP represent a deterministic wind  
 578 profile (no turbulence) modelling the variation of mean wind speed over the rotor using average  
 579 (near-neutral boundary layer) conditions for wind shear and air density. The NWP is used in  
 580 combination with specific controller actions like start-up or shutdown and serves as the basis  
 581 upon which other wind events are added. Uncertainty modelling for the NWP is therefore  
 582 normally not relevant or replaced by other specific wind conditions as e.g. the NTM model.

583 The NTM represent normal stochastic wind (turbulence) conditions using a distribution for the  
 584 turbulence and average conditions for wind shear and air density to model normal operating  
 585 conditions. The stochastic representation of the NTM should according to IEC 61400-1 be based  
 586 on a Weibull distribution  $F_{\sigma_1}(\sigma_1)$  for the wind speed standard deviation  $\sigma_1$  (10min reference  
 587 period) for IEC class verification.

$$F_{\sigma_1}(\sigma_1) = 1 - \exp \left( - \left( \frac{\sigma_1}{C} \right)^k \right) \quad (4)$$

$$k = 0.27 V_{hub}(\text{s/m}) + 1.4 \quad (5)$$

$$C \cong I_{ref}(0.75 V_{hub} + 3.3\text{m/s}) \quad (6)$$

588 where  $C$  and  $k$  are the scale and shape parameter and  $I_{ref}$  is the reference turbulence intensity  
 589 according to IEC 61400-1. The uncertainty modelling for the NTM should cover the natural  
 590 variation of mean wind speed and turbulence. Additionally, the uncertainty modelling may cover  
 591 variations in wind shear, air density and wind direction along with the potential dependence /  
 592 correlation between these due to different atmospheric stability conditions.

### 593 6.2.2.2 Extreme wind conditions

594 The extreme wind conditions are in IEC 61400-1 represented by the Extreme Wind Model  
 595 (EWM), Extreme Operation Gust (EOG), Extreme Turbulence Model (ETM), Extreme Direction  
 596 Change (EDC), Extreme Coherent gust with Direction change (ECD) and Extreme Wind Shear  
 597 (EWS). These events are defined to cover all relevant extreme wind conditions for a wind turbine  
 598 and are defined by extrapolation of a single wind parameter or wind event. The events should  
 599 therefore in general not be combined with variations in other wind conditions.

600 The stochastic models for the extreme wind conditions should correspond to an annual  
 601 reference period when combined with specific operational states e.g. grid-loss, start-up or shut-  
 602 down. This ensures consistency with the target reliability level specified in 5.

603 The EWM represents conditions with extreme wind speeds. The EWM is in IEC 61400-1 defined  
 604 by the maximum 10min mean wind speed with a return period of 1 year and 50 years, which  
 605 represent the characteristic value.

$$V_{50} = V_{ref} \quad (7)$$

606 The uncertainty modelling for the EWM should represent the physical uncertainty in the annual  
607 maximum wind speed which for extratropical storms can be modelled by a Gumbel distribution  
608 with a typical coefficient of variation equal to 12% for IEC class verification.

609 The EOG represents the extreme gust which occurs together with a specific operation event  
610 such as a start-up, shut-down or electrical fault to give a combined return period of 50 years.  
611 The EOG can according to IEC 61400-1 be replaced with the NTM model for DLC 2.3 and by  
612 the ETM model for DLC 3.2 and 4.2 offering an easier combination with specific operational  
613 states.

614 The EOG is in IEC 61400-1 defined by a gust profile expressed in space over the event duration  
615 and described by the gust magnitude  $V_{gust}$  (which for current wind turbine design is defined by  
616 the second term in equation (9)) and duration  $T$ .

$$V_{gust} = \beta \left( \frac{\sigma_1}{1 + 0.1 \left( \frac{D}{\Lambda_1} \right)} \right) \quad (8)$$

$$V(z, t) = \begin{cases} V(z) - 0.37V_{gust} \sin(3\pi t/T)(1 - \cos(2\pi t/T)) & \text{for } 0 \leq t \leq T \\ V(z) & \text{otherwise} \end{cases} \quad (9)$$

617 The uncertainty modelling for the EOG should represent the uncertainty in the annual maximum  
618 gust magnitude and duration. The gust profile can be considered deterministic along with the  
619 parameters  $\Lambda_1$ ,  $D$  and  $\sigma_1$  (90% quantile). The gust magnitude and duration can be assumed  
620 fully correlated and can be modelled by a Gumbel distribution based on the return periods  
621 defined in Table 2. A simplified uncertainty model for the EOG can be obtained by only  
622 modelling the gust magnitude probabilistically, while assuming the duration is deterministic  
623 ( $T=10.5s$ ).

624

**Table 2 – EOG parameters for different return periods.**

Return Period	Gust Magnitude ( $V_{gust}$ )	Duration (T)
IEC 61400-1 Ed.4	$\beta = 3.3$	$T = 10.5s$
1 year	$\beta = 4.8$	$T = 10.5s$
50 year	$\beta = 6.4$	$T = 14.0s$

625 The ETM represents the 50 year extreme turbulence conditions at a given mean wind speed  
626  $V_{hub}$ , based on the Inverse First Order Reliability Method (IFORM) using the models for the  
627 normal wind conditions in 6.2.2.1, see Annex B. Alternatively, the uncertainty model for the  
628 ETM can be represented by the conditional distribution for the annual extreme turbulence at a  
629 given mean wind speed.

630 The EDC represent the extreme direction change which occur together with a specific operation  
631 event such as a start-up with a return period of 50 years. The EDC is in IEC 61400-1 defined  
632 by a wind direction variation, expressed over the event duration, which is described by the  
633 extreme direction change magnitude  $\theta_e$  and duration  $T$ .

$$\theta_e = \pm \beta \arctan \left( \frac{\sigma_1}{V_{hub} \left( 1 + 0.1 \left( \frac{D}{A_1} \right) \right)} \right) \quad (10)$$

$$\theta(t) = \begin{cases} 0^\circ & \text{for } t < 0 \\ \pm 0.5 \theta_e (1 - \cos(\pi t/T)) & \text{for } 0 \leq t \leq T \\ \theta_e & \text{for } t > T \end{cases} \quad (11)$$

634 The uncertainty modelling for the EDC should represent the uncertainty in the annual extreme  
 635 wind direction change. The wind direction profile and duration can be considered deterministic  
 636 along with the parameters  $\Lambda_1$ , D and  $\sigma_1$  (90% quantile). The extreme wind direction change can  
 637 be modelled by a Gumbel distribution based on the return periods defined in Table 3.

638 **Table 3 – EDC parameters for different return periods.**

Return Period	Extreme Direction Change ( $\theta_e$ )	Duration (T)
IEC 61400-1 Ed. 4	$\beta = 4.0$	T = 6s
1 year	$\beta = 4.8$	T = 6s
50 year	$\beta = 6.4$	T = 6s

639 The ECD represents the 50 year extreme coherent gust with direction change occurring during  
 640 normal operating conditions. The ECD is in IEC 61400-1 defined by a gust and wind direction  
 641 variation, expressed over the event duration, which is described by the coherent gust magnitude  
 642  $V_{cg}$ , wind direction change magnitude  $\theta_{cg}$  and duration T.

$$V(z, t) = \begin{cases} V(z) & \text{for } t < 0 \\ V(z) \pm 0.5 V_{cg} (1 - \cos(\pi t/T)) & \text{for } 0 \leq t \leq T \\ V(z) + V_{cg} & \text{for } t > T \end{cases} \quad (12)$$

$$\theta_{cg} = \begin{cases} 180^\circ & \text{for } V_{hub} < 4m/s \\ 720^\circ & \text{for } 4m/s < V_{hub} < V_{ref} \\ \frac{720^\circ}{V_{hub}} & \end{cases} \quad (13)$$

$$\theta(t) = \begin{cases} 0^\circ & \text{for } t < 0 \\ \pm 0.5 \theta_{cg} (1 - \cos(\pi t/T)) & \text{for } 0 \leq t \leq T \\ \pm \theta_{cg} & \text{for } t > T \end{cases} \quad (14)$$

643 The uncertainty modelling for the ECD should represent the uncertainty in the annual extreme  
 644 coherent gust and wind direction change. The gust profile, wind direction profile and duration  
 645 (T=10s) can be considered deterministic. The annual extreme coherent gust magnitude and  
 646 wind direction change can be assumed fully correlated and can be modelled by a Gumbel  
 647 distribution with a coefficient of variation of 10%.

648 The EWS represents the 50 year extreme transient events with horizontal and vertical wind  
 649 shear. The EWS is in IEC 61400-1 defined by a wind speed profile for the event duration, which  
 650 is described by the wind shear magnitude parameter  $\beta$  and duration T.

651 Transient (positive and negative) vertical shear:

$$V(z, t) = \begin{cases} V_{hub} \left( \frac{z}{z_{hub}} \right)^\alpha \pm \left( \frac{z - z_{hub}}{D} \right) \left( 2.5 \left[ \frac{m}{s} \right] + 0.2 \beta \sigma_1 \left( \frac{D}{\Lambda_1} \right)^{1/4} \right) (1 - \cos(2\pi t/T)) & \text{for } 0 \leq t \leq T \\ V_{hub} \left( \frac{z}{z_{hub}} \right)^\alpha & \text{otherwise} \end{cases} \quad (15)$$

652 Transient horizontal shear:

$$V(y, z, t) = \begin{cases} V_{hub} \left( \frac{z}{z_{hub}} \right)^\alpha \pm \left( \frac{y}{D} \right) \left( 2.5 \left[ \frac{m}{s} \right] + 0.2 \beta \sigma_1 \left( \frac{D}{\Lambda_1} \right)^{1/4} \right) (1 - \cos(2\pi t/T)) & \text{for } 0 \leq t \leq T \\ V_{hub} \left( \frac{z}{z_{hub}} \right)^\alpha & \text{otherwise} \end{cases} \quad (16)$$

653 The uncertainty modelling for the EWS should represent the uncertainty in the annual extreme  
654 horizontal and vertical wind shear magnitude. The wind speed profile and duration can be  
655 considered deterministic along with the parameters  $\Lambda_1$ ,  $D$  and  $\sigma_1$  (90% quantile). The annual  
656 extreme horizontal and vertical wind shear magnitude parameter  $\beta$  can be modelled by a  
657 Gumbel distribution based on the return periods defined in Table 4.

658 **Table 4 – EWS parameters for different return periods.**

Return Period	Extreme Wind shear magnitude	Duration (T)
IEC 61400-1 Ed. 4	$\beta = 6.4$	T = 12s
1 year	$\beta = 4.8$	T = 12s
50 year	$\beta = 6.4$	T = 12s

### 659 6.2.3 Other conditions

660 Other atmospheric conditions include e.g. wake conditions, tropical cyclones, ice formation and  
661 extreme temperatures are listed in IEC 61400-1 and IEC 61400-3-1.

662 Wake conditions may be modelled according to IEC 61400-1 Annex E. The model uncertainty  
663 related to the wake modelling should represent the fidelity and validation of the model, see 6.3.  
664 Additionally, the physical and statistical uncertainty in the wake conditions and the frequency  
665 of their occurrence should be considered.

666 Tropical cyclone conditions may be represented by the Extreme Wind Model (EWM), but the  
667 coefficient of variation (COV) for the annual extreme wind speed / pressure is normally higher  
668 than for other extreme wind conditions and should therefore be representative for these events.

669 Ice formation may be modelled according to IEC 61400-1 Annex L. The physical and model  
670 uncertainty in the accretion of ice or snow on the structure should be considered along with the  
671 frequency of occurrence.

672 The additional environmental conditions listed in IEC 61400-1 and IEC 61400-3-1 (with the  
673 exception of earthquakes and tsunamis) can in most probabilistic analysis be represented by a  
674 deterministic value corresponding to the expected value or a low / high quantile. In case the  
675 additional environmental conditions have a significant impact on the probabilistic analysis,  
676 stochastic models should be established.

#### 677 6.2.3.1 Earthquakes

678 Earthquakes generate loads in terms of ground acceleration acting at the foundation of a wind  
679 turbine, which is specified by a spectrum at a given return period. IEC 61400-1 specifies the  
680 load level for design with a return period of 475 years and defines superposition with other

681 loads and associated safety factors. The widely used return period of 475 years corresponds to a 10% probability of exceedance in 50 years.

683 Seismic loading is highly dependent on local conditions and is defined in seismic codes, which often demand, besides prescription of the load spectrum the use of certain models for assessment of structural earthquake resistance.

686 Typically, probabilistic seismic hazard analyses (PSHA) are carried out in order to define relevant seismic loading for a specific wind turbine site. By use of PSHA, the probability of exceedance of a specified level of ground motion can be calculated.

#### 689 **6.2.4 Electrical network conditions**

690 The external electrical conditions at the wind turbine terminals influence the reliability of both electrical and mechanical components dependent on the design of the energy conversion system.

693 IEC 61400-1 provides guidance on the types of electrical network conditions. Statistics on such conditions are not commonly available and vary from country to country. National grid utilities provide some information publicly or on demand. Furthermore, measurements at wind turbine sites can provide data for defining appropriate discrete or continuous distributions.

697 An example for application of continuous distribution is the range of grid voltage and frequency as an occurrence probability distribution.

699 Discrete distributions are more suited for less frequent conditions, such as, for example, power ramps, temporary derating, grid loss and fault ride through (FRT) events.

701 The latter two, grid loss and FRT, are part of the standard load case definitions in IEC 61400-1. While grid loss is fully defined by its occurrence rate, FRT events have a number of other attributes that needs to be considered such as magnitude and length of the voltage drop or peak, level of symmetry and number of consecutive events. These attributes can have a significant load effect on both, the mechanical and the electrical system. Modelling these attributes requires appropriate information on the occurrence distribution as well as on suitable binning of the event types.

### 708 **6.3 Load uncertainty modelling**

#### 709 **6.3.1 General**

710 The load uncertainty modelling refers to the uncertainties in the assessment of the load on the individual wind turbine components and subcomponents. Typically, the following steps are followed in load assessments, see also Figure 2:

713 a) Input to the aeroelastic model (such as external conditions, structural design, aerodynamics and wind turbine controller) is defined.

715 b) The direct outcome of the aeroelastic simulations are time series of section forces in components (modelled as finite elements in the aeroelastic simulations), for combinations of the input variables.

718 c) Relevant loads are extracted from the timeseries for each considered load case using appropriate methods (e.g. extreme values, rainflow cycle counting and Markov matrix).

720 d) Extracted loads are combined with their probability of occurrence to obtain the long-term distributions.

721

722 e) Load effects in critical locations of components are estimated using transfer functions  
723 based on FEM or analytical/empirical formulations.

724 As part of the probabilistic load assessment, uncertainties in all steps should be considered  
725 and included. The assessment of uncertainties should be performed in relation to relevant limit  
726 state equations for selected components, failure modes and design load cases.

### 727 6.3.2 Aeroelastic Model

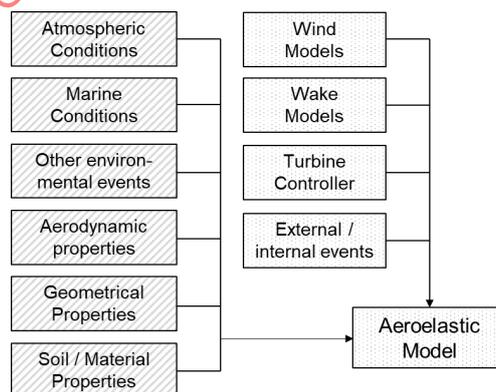
728 Uncertainty on the input to the aeroelastic model (see Figure 6.2) cause uncertainties on the  
729 output. Therefore, uncertainties related to the input should be quantified on the base level and  
730 propagated through the computational models used in the load assessment. This includes  
731 uncertainties in the assessment of section forces using an aeroelastic model and if relevant  
732 assessment of load effects based on section forces using FEM models or analytical models.  
733 The formulation of the uncertainty model should consider the influence of nonlinearities in the  
734 relation between section forces and load effects.

735 The uncertainty propagation can be performed by simulation-based methods (Monte-Carlo,  
736 Importance Sampling) or local expansion methods (Taylor series) to determine the resulting  
737 model uncertainty for the considered component, failure mode and design load case. The  
738 uncertainty propagation should take any potential correlation between uncertainties in the input  
739 parameters into account. The convergence of the uncertainty propagation should be assessed.  
740 The uncertainty propagation can be performed with simplified simulations models like e.g.  
741 surrogate models.

742 For some input to the aeroelastic model, it is not possible to propagate the uncertainties (e.g.  
743 model choices) through the aeroelastic model. The uncertainty in these inputs should therefore  
744 be quantified based on measurements, model variations or subjective information and  
745 represented by model uncertainties, see equation (17), Figure 1 and Annex A.

$$Y = X_{Model} \cdot M(X, \theta) \quad (17)$$

746 A typical split between the uncertainties which should be propagated through the aeroelastic  
747 model (shaded) and those which should be represented by model uncertainty (dotted) is shown  
748 in Figure 3.



749

750 **Figure 3 – Typical split between uncertainties which should be propagated through the**  
751 **aeroelastic model (shaded) and those which should be represented by model**  
752 **uncertainty (dotted), see also the typical flow chart in Figure 2.**

753 Other contributors to the aeroelastic model uncertainty are uncertainties related to the methods  
754 used for wind turbine modelling and simulation (e.g. BEM theory, multibody, FEM), the  
755 discretization in finite elements (degrees of freedom) and time domain (simulation time steps).

756 The model uncertainty related to the aeroelastic model will in general be dependent on the  
757 fidelity and validation of the model applied. The model uncertainty may be determined based  
758 on load measurements and validation campaigns from e.g. proto-type turbines according to IEC  
759 61400-13, where measurement load cases corresponding to the design load cases are defined.

760 The model uncertainty for the aeroelastic model with respect to extreme loads may be  
761 determined based on 10-minute statistics (min, max, mean, std) from the measurement load  
762 cases defined in IEC 61400-13<sup>3</sup>. The model uncertainty with respect to fatigue loads may be  
763 determined based on 10-minute damage equivalent loads (DEL). The model uncertainty may  
764 be determined based on Annex A.3, but measurement uncertainty will typically be included in  
765 the assessment, potentially together with other model uncertainties listed in Figure 2 and  
766 Figure 3.

767 The assessment of the model uncertainty should focus on the considered design situation,  
768 components, and environmental conditions of interest. Statistical uncertainty due to the limited  
769 amount of measurement / validation data available should be considered if the data  
770 requirements in IEC 61400-13 are not fulfilled.

771 If the uncertainty propagation or assessment of model uncertainties have been performed for a  
772 specific component, failure mode or design load case, the resulting model uncertainty may be  
773 re-used for similar wind turbine types and design situations when appropriately justified.

### 774 6.3.3 Extreme loads

775 The estimated extreme loads are dependent on the number of simulations and consideration  
776 should be given to the convergence criteria and the statistical uncertainty related to the  
777 assessment. The extreme loads are normally assessed using one of the following methods:

- 778 • Extrapolation methods typically involving peak extraction or Inverse First-Order  
779 Reliability Methods (IFORM). The independence of the peaks and goodness of fit for  
780 the distribution function used to determine the exceedance probability of e.g. 50 years  
781 should be evaluated.
- 782 • Averaging methods where the extreme load is determined using a specific averaging  
783 scheme (e.g. mean value of the largest half) of the peak values from each time series.  
784 The statistical uncertainty related to the number of simulations should be evaluated.
- 785 • (Prototype / field measurements where the uncertainty related to the aeroelastic model  
786 is omitted, but measurement uncertainties are introduced. The statistical uncertainty  
787 related to the number of measurements should be evaluated.)

### 788 6.3.4 Fatigue loads

789 Fatigue damage occurs from an accumulation of cycles due to the fluctuating loads. The fatigue  
790 loads are for structural components normally represented by the number of load cycles with  
791 different ranges and mean load levels extracted by e.g. the rainflow cycle counting method,  
792 whereas the fatigue loads for mechanical components normally are represented by the time  
793 different load levels occur represented by duration loads.

794 The model and statistical uncertainty related to the fatigue load assessment should be  
795 evaluated. The model uncertainty related to the fatigue load assessment (e.g. rainflow cycle  
796 counting) is normally assessed together with the model uncertainty for the fatigue damage  
797 assessment (e.g. Miner's Rule) and represented by a single model uncertainty.

---

<sup>3</sup> In addition detrending of turbulence may be considered to apply to load cases given in IEC 61400-1.

## 798 **6.4 Structural resistance uncertainty modelling**

### 799 **6.4.1 General**

800 The uncertainty in structural resistance is in general dependent on the variation in geometrical  
801 and material properties, resistance models along with the manufacturing methods and quality.

802 The structural resistance shall according to IEC 61400-1 be analysed for the following limit  
803 states where relevant:

- 804 • Analysis of ultimate strength
- 805 • Analysis of fatigue failure
- 806 • Stability analysis
- 807 • Critical deflection analysis

808 Each type of analysis requires a different formulation of the limit state function and deals with  
809 different sources of uncertainties, see 6.1.1. The limit state function can in general be  
810 formulated based on the design requirements for the individual component specified in e.g. IEC  
811 61400-1, IEC 61400-6 or IEC 61400-8.

812 Further guidance on the assessment of uncertainties, characteristic values and partial safety  
813 factors for structural resistance is given IEC 61400-1 Annex K.

### 814 **6.4.2 Geometrical properties**

815 The uncertainty in geometrical properties can either be estimated based on observations /  
816 measurements or the manufacturing tolerance specification defined for the considered  
817 component along with the applied quality control.

818 The uncertainty in geometrical properties is for most wind turbine components small and has  
819 therefore normally minor effect on the structural resistance. If this is justified the geometrical  
820 properties can be modelled deterministic in the limit state function.

### 821 **6.4.3 Material properties**

822 The uncertainty and potential bias in the material properties can either be estimated based on  
823 measurements or the manufacturing / supplier specifications for the considered material along  
824 with the applied quality control.

825 The uncertainty modelling for the material properties and the associated structural resistance  
826 should consider the failure mode (brittle vs. ductile), scale effects and degradation during the  
827 design lifetime.

### 828 **6.4.4 Resistance models**

829 The resistance model can either represent the structural resistance as a mathematical model  
830 which is dependent of e.g. geometrical and material properties (Model 1 and 2 in IEC 61400-1  
831 Annex K .3) or alternative specify the structural resistance directly based on e.g. tests (Model  
832 3 in IEC 61400-1 Annex K.3).

833 When the resistance model is a mathematical model the model uncertainty and potential bias  
834 should be estimated based on component tests using the statistical method described in  
835 Annex A and IEC 61400-1 Annex K.12. In situations where component tests are not available

836 and/or not practical possible to obtain, higher fidelity models can be used to assess the model  
837 uncertainty and potential bias in the resistance model, but model uncertainty related to the  
838 higher fidelity model should be considered.

839 When the resistance model specifies the structural resistance directly the physical uncertainty  
840 and potential bias should be estimated based measurements.

#### 841 **6.4.5 Fatigue strength and damage accumulation**

842 The uncertainty in the fatigue strength can either be estimated based on measurements or the  
843 manufacturing / supplier specifications for the considered material along with the applied quality  
844 control. In IEC 61400-1 section 7.6.3.3 typical coefficient of variations are specified for different  
845 materials.

846 The fatigue strength is often determined based on a limited number of measurements. Bayesian  
847 statistical methods can be applied in order to incorporate the knowledge obtained from past  
848 measurements with a similar material / component.

849 The model uncertainty related to fatigue cycle counting and fatigue damage accumulation  
850 should be considered. A correction for the mean stress level should be applied for materials  
851 where the mean stress level significantly influences the fatigue strength.

#### 852 **6.5 Component reliability uncertainty modelling**

853 The reliability of a component or the probability for different fault situations on the wind turbine  
854 is often determined from historical data and described by the time to failure distribution or failure  
855 rates.

856 Component reliability modelling is normally applied to electrical and mechanical components,  
857 where the time to failure often is modelled by a Weibull distribution, whose parameters are  
858 determined based on failure statistics. Model uncertainty should represent the deviations  
859 between the failure statistics and the actual component and application (component generation,  
860 environment, loading conditions, etc.). Statistical uncertainty should represent the sample size  
861 for the failure statistics.

862 The reliability for different fault situations can in structural reliability analysis e.g. be modelled  
863 by formulating a limit state equation conditional on the fault.  
864

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## 865 7 Performance modelling

### 866 7.1 General

867 For components, failure modes and DLCs selected for probabilistic design, limit state equations  
868 shall be formulated allowing for the calculation of the annual failure probability. Guidance is  
869 provided to formulate conditional limit states and in relation to different design load cases  
870 (DLC's).

871 Combinations of mechanical loads acting on the turbine structures shall be considered to ensure  
872 structural performance based on the load cases specified in the IEC 61400-1 and IEC 61400-3  
873 as applicable.

### 874 7.2 Structural performance of primary structures

875 All relevant limit states shall be evaluated, which may also include serviceability limit states and  
876 accidental situations. Return periods of extreme events for ultimate limit state analysis may be  
877 evaluated with suitable measurements and past historical data. Load evaluation is made  
878 primarily through the results of the aeroelastic simulations. The effects of consequence classes  
879 on the conditions can also be directly included.

880 In the following is described the basis for deriving probabilistic models for structural  
881 performance modelling and how to adapt the probabilistic models to the semi-probabilistic  
882 models in IEC 61400-1 and IEC 61400-3 where the models may be characterized by a certain  
883 return period, typically 50 years.

#### 884 7.2.1 Load Performance calibration for ultimate limit states

885 This subsection details the computation of the probability of failure under extreme load cases and fatigue  
886 load cases and develops a procedure for quantifying the probability of failure, given external conditions.  
887 Defining DLCs for the load effect for known specific site conditions and frequency of occurrences of  
888 faults can be designed using probabilistic methods. This allows that the inputs to load cases can be  
889 tailored to a specified annual probability of failure or joint return period. Annual failure probability  
890 obtained by limit state equations with annual extreme load effect.

891 For limit state equations  $g(\cdot)$  formulated using the distribution for the extreme annual load effect  
892  $L$ , the annual failure probability  $P_f$  is calculated from:

$$P_f = P(g(L, X) \leq 0) \quad (18)$$

893 where  $X$  is the set of stochastic variables for resistance and model uncertainties, and  $L$  is the  
894 extreme annual load effect described by the distribution function  $F_L(L)$ . To obtain the distribution  
895  $F_L(L)$ , the following steps are generally followed: a) Run aeroelastic simulations for relevant  
896 ranges of environmental conditions and other conditions required in the DLC, b) extract extreme  
897 load effects from generated time series, and c) estimate the distribution for the extreme annual  
898 load effect by fitting and aggregation over environmental conditions (in either order).

899 This approach assumes that resistance and model uncertainties are time-invariant.

#### 900 7.2.1.1 Annual failure probability obtained by conditional failure probabilities

901 For load cases with discrete events (deterministic wind field events, fault events or operational  
902 events (start-up / shutdown)) (such as DLC 1.4, 1.5, 2.1, 2.2, 2.3, 2.5, 3.3, 4.2, 5.1), the  
903 probability of failure given an event  $E$  is calculated from the limit state equation:

$$P_{f|E} = P(g(L_E, X) \leq 0) \quad (19)$$

904 where  $L_E$  is the extreme load effect during event  $E$ , described by the distribution  $F_{L_E}(L_E)$ , which  
 905 is found by aggregation over the relevant environmental conditions.

906 Instead of combining various environmental conditions (or other conditions) in the distribution  
 907  $F_{L_E}(L_E)$ , the conditional probability of failure may be calculated conditioned on specific  
 908 environmental conditions,  $c$  and mean wind speed  $V$ , in which case, the limit state equation is  
 909 written:

$$P_{f|E,v,c} = P(g(L_E(V, c), X) \leq 0) \quad (20)$$

910

911 **7.2.1.2 Description of annual failure probability conditioned on specific**  
 912 **environmental conditions**

913 The characteristic load exceedance probability shall be determined for environmental  
 914 conditions given in 6.2, whereby the probability of failure of the structure can be directly  
 915 assessed. Applying Eq. (23) with  $g(L_E(V, c), X)$  substituted as  $R(X) - L(X, V, c, E)$ ,

916 The probability of failure conditional on an event  $E$  occurring at specified environmental  
 917 conditions is computed by:

$$P_{f|E} = \int_0^{\infty} \int_{-\infty}^{\infty} P(R(X) - L(X, V, c, E) \leq 0) p(V, c, E) dc dV \quad (21)$$

$$p(V, c, E) = p_{E|c,V}(E|c, V) \cdot p_{c|V}(c|V) \cdot p(V)$$

918 where  $X$  are the set of random parameters representing material and loads uncertainties,  
 919  $L(X, V, c, E)$  is the extreme load effect conditional on an event,  $E$  and the environmental quantities  
 920 of interest,  $p(V, c, E)$  is the joint probability of the mean wind speed ( $V$ ), environmental variable  
 921 of interest ( $c$ ), such as turbulence and an event, and  $R$  is the structural resistance given in  
 922 terms of load level, such as bending moment corresponding to a failure stress. Uncertainties in  
 923 the material properties and loads are to be included in the probability distributions for  $R$  and  $L$   
 924 respectively as per 6.3 and 6.4 and equation (21). can be solved, for example using Monte-  
 925 Carlo simulations. The resulting failure probability can be determined thereby for a given  
 926 structure using a set of extreme loads obtained from the output of aeroelastic simulations using  
 927 a set of environmental conditions as input.

928 As a special case of Eq. (24), in some ultimate limit state cases, (Example: blade strike of a  
 929 tower, stress hotspot dependent on load direction etc.), the probability of the direction of the  
 930 load or deflection,  $\theta$  is also required to be considered in equation (21), in which case, the  
 931 probability of failure can be written as:

$$P_{f|E} = \int_{-\infty}^{\infty} \int_0^{\infty} \int_0^{2\pi} (P(R(\theta, X) - L(\theta, X, V, c, E) \leq 0) p(V, c, E) d\theta dV dc \quad (22)$$

932 In the absence of an event,  $E$ ,  $p(V, c, E)$  in equations (21) and (22) is replaced with  $p(V, c)$  and  
 933 the corresponding load probability distribution over the environmental conditions ( $V, c$ ) is  
 934 utilized.

935 Further details and examples on the formulation of environmental conditions and limit states  
 936 with conditional events or independent events (Example: DLC 2.x from IEC 61400-1) are given  
 937 in Annex D.

938 If fault events, internal or external to the wind turbine, are not fully dependent on specific  
 939 environmental conditions, then the annual failure rate ( $\lambda_F$ ) may be estimated based on a  
 940 numerical integration (binning), by combining conditional probability of failure given an event  $E$ ,  
 941 while specifying the rate of events  $\lambda_E$ , as:

$$\lambda_F = \sum_{V,c} P_{F|E,v,c} \lambda_E(V,c) P(c|V) P(V) \quad (23)$$

942 where the occurrence of events  $E$  is expressed through the rate  $\lambda_E(V,c)$  of the event given  
 943 environmental condition  $c$  occurring with probability  $P(c|V)$  and mean wind speed  $V$  occurring  
 944 with probability  $P(V)$ . It is further noted that, for small values of annual failure rate ( $\lambda_F \leq 0.02$ ),  
 945 the annual failure probability may be approximated by the numerical value of the failure rate:

$$946 \quad P_f \approx \lambda_F, \quad \lambda_F \leq 0.02$$

### 947 7.2.1.3 Load Performance calibration for Fatigue limit states

948 Wind turbine operational cases and situations with shutdowns, stand still, start-ups should be  
 949 evaluated to determine their individual influence towards fatigue damage. Equivalent turbulence  
 950 level, wind/wave misalignment can be calibrated to specific structures, where the full probability  
 951 distribution of the environmental conditions is not used in the load simulations. At a minimum  
 952 the distribution of wind turbulence, the distribution of significant wave height and peak spectral  
 953 period for offshore structures shall be considered conditional or jointly with the probability of  
 954 the mean wind speed. IEC 61400-1 or 61400-3 load cases for fatigue that consider events or  
 955 turbine stand-still should consider the probability of occurrence of those events or the duration  
 956 of stand-still in the assessment of fatigue damage.

957 The allowable material properties in the fatigue analysis should be based on standardized tests.  
 958 The material behaviour under fatigue should be modelled by an appropriate distribution with the  
 959 mean value and coefficient of variation obtained through standardized tests. In the absence of  
 960 such data, the distribution function can be estimated based on the characteristic material values  
 961 and appropriate assumptions on the standard deviation.

962 An appropriate fatigue limit state such as the Miners sum may be used to model the material  
 963 failure under fatigue. The distribution of the Miner sum upon failure may be assumed to  
 964 lognormally distributed. The limit state analysis for fatigue shall include probability distributions  
 965 for the stress amplitude and for the material resistance. Uncertainties on dependent variables  
 966 such as stress concentration factors, geometric effects, surface finish etc. will also be  
 967 accounted for where appropriate. The component stress cycles should be obtained through the  
 968 simulation of appropriate load cases from the IEC 61400-1 using either the full distribution of  
 969 wind turbulence or at the 90% turbulence value. The annual probability of failure in year  $t$ ,  
 970 conditional on survival until that year is estimated by:

$$\Delta P_f(t) = \frac{P(g(t) \leq 0) - P(g(t - \Delta t) \leq 0)}{1 - P(g(t - \Delta t) \leq 0)} \quad (24)$$

971 Where  $g(t)$  is the fatigue limit state equation of the material in a given year,  $t$  and  $\Delta t = 1$  year.

### 972 7.2.2 Evaluation of Serviceability limit states

973 Serviceability limit states concern the response of the wind turbine structures during normal  
 974 functioning of the structure under normal use, long term functioning and appearance. For  
 975 reliability based design, the annual probability of failure under serviceability limit state shall be  
 976 utilized based on the values stipulated in section 5, unless specific instances require another  
 977 probability of failure based on historical data. For concrete structures, the serviceability limit

978 state can involve maximum allowable crack sizes and sliding of the concrete layers, such as for  
979 a grouted joint and care should be taken that the evaluation of this limit state includes adequate  
980 representation of the material behaviour. The serviceability analysis of fixed support structures  
981 shall follow appropriate standards such as the IEC 61400-6.

982 The load cases in the IEC 61400-1 towards ultimate limit state can be considered for  
983 serviceability limit states also. For serviceability analysis of response behaviour, the partial load  
984 factors and partial resistance factors shall be taken as unity in the partial factor design method.

### 985 **7.3 Performance of primary mechanical and electrical components**

986 The performance requirements of mechanical or electrical components requires additional  
987 assessments such as thermal effects, lubrication quality, hydraulic pressure, friction effects,  
988 that are not considered in the performance of primary structures. The performance of  
989 components in the primary load path such as the bedplate, generator, gearbox casing, hub etc.  
990 shall be made considering relevant design load cases in IEC 61400-1 in conjunction with the  
991 requirements in other relevant standards such as the IEC 61400-4 and IEC 61400-8. The load  
992 effect modelling may require the use of additional appropriate software on top of aeroelastic  
993 tools. Electro-mechanical modelling of the drivetrain may be necessary to evaluate its structural  
994 performance. The structural integrity of individual elements shall be verified by taking into  
995 consideration all its boundary conditions and adjacent connections. Additional fail-safe  
996 components may be evaluated without the need for added partial safety factors in loading.  
997 Control and protection systems shall be assessed according to the required mean time between  
998 failures (MTBF). The MTBF can either be a requirement from a risk assessment or a result of  
999 the application of IEC 61400-1 Table 3.

#### 1000 **7.3.1 Requirements for mechanical components**

1001 Reference to section 9 of the IEC 61400-1 is made in terms of description of essential  
1002 mechanical components and systems. Stresses in mechanical components will be adequately  
1003 modelled for appropriate limit states analysis and these may involve stress components not  
1004 considered in structural design, such as Hertzian contact stresses at an interface and hoop  
1005 stresses in bearing rings where reference is made to IEC 61400-4. The limit state equations for  
1006 mechanical components used in its design shall be based on critical failure modes of that  
1007 component and include the effects of ambient conditions on its material properties. If the  
1008 mechanical component is in the primary load path of the wind turbine, then a target annual  
1009 probability of failure as specified in chapter 5 is to be used. Higher annual probabilities of failure  
1010 may be used where the failure of the component does not result in a critical failure of the wind  
1011 turbine.

#### 1012 **7.3.2 Serviceability limit states for mechanical components**

1013 Mechanical component such as bearings, bolts, gears etc, shall be evaluated for applicable  
1014 serviceability limit states, examples of which include allowable deflection of bearings, sliding of  
1015 bolts and temperatures in the gearbox or generator. Such limit states shall be assessed  
1016 considering all relevant load cases.

#### 1017 **7.3.3 Requirements for electrical components and control and protection systems**

1018 A Failure Mode Effects Analysis (FMEA) shall be used to determine the type of failures and the  
1019 need for further analysis of the annual probability of failure of control and protection systems in  
1020 accordance with IEC 61400-1, section 8.4. Protection functions shall be designed minimizing  
1021 the probability of the identified failures or their consequences sufficiently. Control and protection  
1022 systems should possess sufficient redundancy so that a single failure of a component within a  
1023 control and protection unit shall not result in loss of protection for the wind turbine. Load cases  
1024 DLC 2.x in the IEC 61400-1 deal with loss of control and protection systems and these should  
1025 be run considering the annual probability of occurrence of their respective events. Equations  
1026 (19), (20) and (21) can be used to calibrate the load case parameters to a target probability of  
1027 failure or to a given return period of environmental conditions, if the mean time between failures

1028 (MTBF) of control and protection systems is known or the frequency of occurrence of a fault is  
1029 known. The MTBF can also be calibrated to a given partial safety factor for loads as described  
1030 in IEC 61400-1 Table 3. Beside the hardware related MTBF, software failures shall be included  
1031 within the scope of the failure analysis.

1032 Electrical components of the wind turbine such as the generator, converter, transformer, as well  
1033 as batteries and motors that drive individual units shall comply with the requirements made in  
1034 IEC 61400-1 section 10 on electrical systems.

#### 1035 **7.3.3.1 Modelling of grid events**

1036 Wind farms are required to comply to grid codes as required for various regions. Specific  
1037 situations such as Low Voltage Ride Through (LVRT) as per DLC 2.5 in the IEC 61400-1 can  
1038 affect the design loads on the turbine structures. In these situations, equation can be used to  
1039 determine the probability of failure of a specific structure or component and thereby calibrate  
1040 the return period of the grid event to be within design specifications. For example, if the turbine  
1041 is designed to withstand extremes with a maximum expected return period of 50-years, then  
1042 equation (21) can be used to ascertain that the loads from the grid event conform to the  
1043 specified return period or exceed that period.

### 1044 **7.4 Robustness of sub-systems**

1045 The Robustness verification of each sub-system includes the following cases:

- 1046 • Accidental limit states
- 1047 • Large environmental effects offshore
- 1048 • Redundancy of components
- 1049 • Sensor redundancy when present for the detection of faulty behaviour

1050 In relation to robustness the following adverse (failure) events are considered

- 1051 - identified accidental actions
- 1052 - unforeseen adverse events

1053 Design approaches for identified accidental actions

- 1054 - design the wind turbine incl. substructure to resist the action
- 1055 - prevent or reduce the action e.g. protective measures, control of events

1056 Design for identified accidental actions shall be undertaken in accordance with a relevant standard.

1057 Note: an example of an identified accidental action is collision of a ship with an offshore wind turbine.

1058 A wind turbine / wind turbine farm system shall be designed and operated to prevent  
1059 disproportionate consequences, as a result of unforeseen adverse events such as the failure  
1060 or collapse of a structural member or part of a wind turbine including the substructure, or to  
1061 provide additional structural resistance to reduce the likelihood and extent of such an event.

1062 Note: Progressive collapse of mooring lines of a floating wind turbine is an example of a damage  
1063 that is disproportionate to the original cause. Increased robustness may be obtained by a design  
1064 with increased redundancy and ductility.

1065

1066 **8 Assessment of reliability**

1067 **8.1 General**

1068 The estimation of the reliability of a structure for a given failure mode is obtained based on the  
1069 associated limit state equation, where all stochastic variables are well characterized.

1070 Section 6 provides guidance on general characterization of uncertainties and stochastic  
1071 variables of interest for wind turbine design and safety assessment, while Section 7 details on  
1072 how to formulate limit state equations for various failure modes and design situations. The  
1073 current section provides guidance on how to perform the last step of assessing reliability both  
1074 for direct reliability design (where the structural design parameter is directly calculated to  
1075 satisfied a given target reliability) as well as for performing calibration of safety factors.

1076 **8.1.1 Reliability measures**

1077 A standard reliability measure may be chosen to be the generalized reliability index  $\beta$  defined  
1078 as

$$\beta = -\Phi^{-1}(P_f) \tag{25}$$

1079 where  $P_f$  is the probability of failure and  $\Phi^{-1}(\cdot)$  is the inverse normal cumulative distribution.

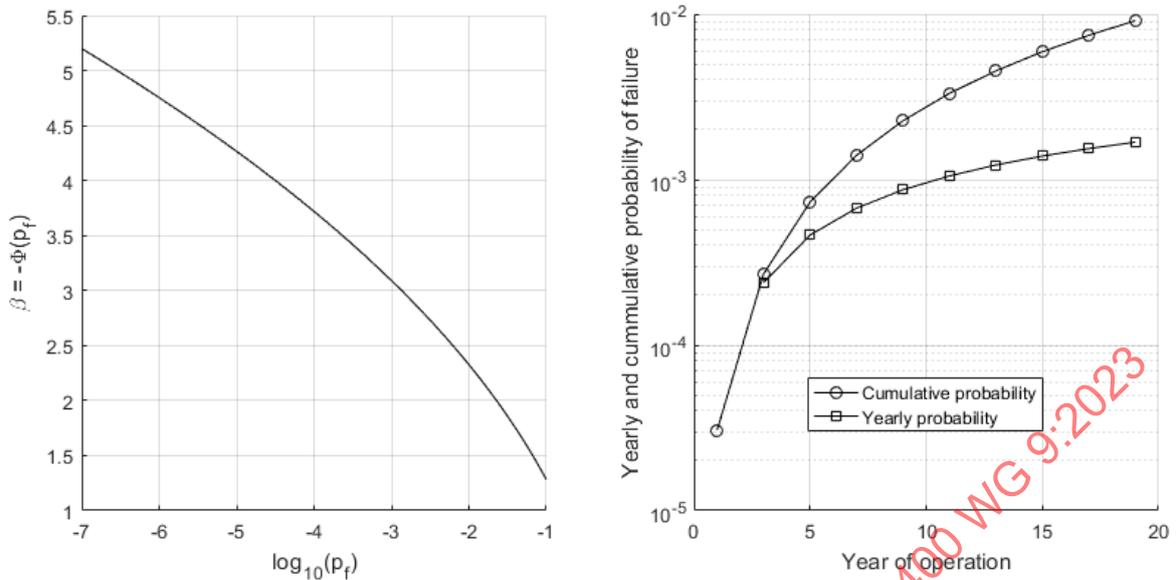
1080 Another equivalent reliability measure is the complement of the probability of failure, the  
1081 *Probability of Survival*  $P_s$

$$P_s = 1 - P_f \tag{26}$$

1082 In many cases the failure probability of a structure is time dependent either due to deterioration  
1083 of the structure resistance over time or because the load is a time-varying stochastic process.  
1084 Particularly in the case of fatigue limit state analysis, one is often concerned with the probability  
1085 of failure during the  $n^{th}$  year of operation given survival up to the  $n^{th}$  year, which is given by  
1086 (24).

1087 Illustrations of such reliability measures are provided in Figure 4.

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1088

1089 **Figure 4 – Measures of reliability. (a) The reliability index as a function of the power of**  
 1090 **failure probability and (b) the cumulative probability of fatigue failure compared to the**  
 1091 **resulting yearly probability of failure**

### 1092 8.1.2 Computation of failure probability

1093 The failure probability of a structural component with respect to a single failure mode is

$$P_f = \int_{g(X) \leq 0} f_X(X) dX \quad (27)$$

1094 where:

$X$  is the vector of basic random variables

$g(X)$  is the limit state function for the failure mode considered

$f_X(X)$  is the joint probability density function of  $X$

1095 An important class of limit states are those for which all the variables are treated as time  
 1096 independent, either by neglecting time variations in cases where this is considered acceptable  
 1097 or by transforming time-dependent random processes into random variables (e.g., by using  
 1098 extreme value distributions). Typical formulations for extreme loading ultimate limit states follow  
 1099 the approach of using extreme value distributions, which is what will be considered in this  
 1100 Section.

1101 The designer is free to choose any calculation method capable of solving the integral in equation  
 1102 (27). As the direct evaluation of the probability integration is usually impractical for real  
 1103 engineering applications, there are a few numerical methods the designer can refer to. The  
 1104 structural reliability methods most used for calculating  $P_f$  are divided into *asymptotic*  
 1105 *approximate* methods, of which the first and second order reliability methods - FORM and  
 1106 SORM respectively – are the most common examples and *simulation methods* such as direct  
 1107 Monte-Carlo simulations, importance sampling, and directional simulation.

1108 First Order Reliability Methods (FORM) can be used to estimate the probability of failure and  
 1109 the reliability index  $\beta$  and due to its common application, a brief overview of the method is  
 1110 presented as follows. The first step is to simplify the integrand  $f_X(X)$  through a variable change

1111 from the “physical” X-space to the standard normal U-space by use of the Rosenblatt  
 1112 transformation (Rosenblatt 1952):

$$U_i = \Phi^{-1}[F_{X_i}(X_i)] \tag{28}$$

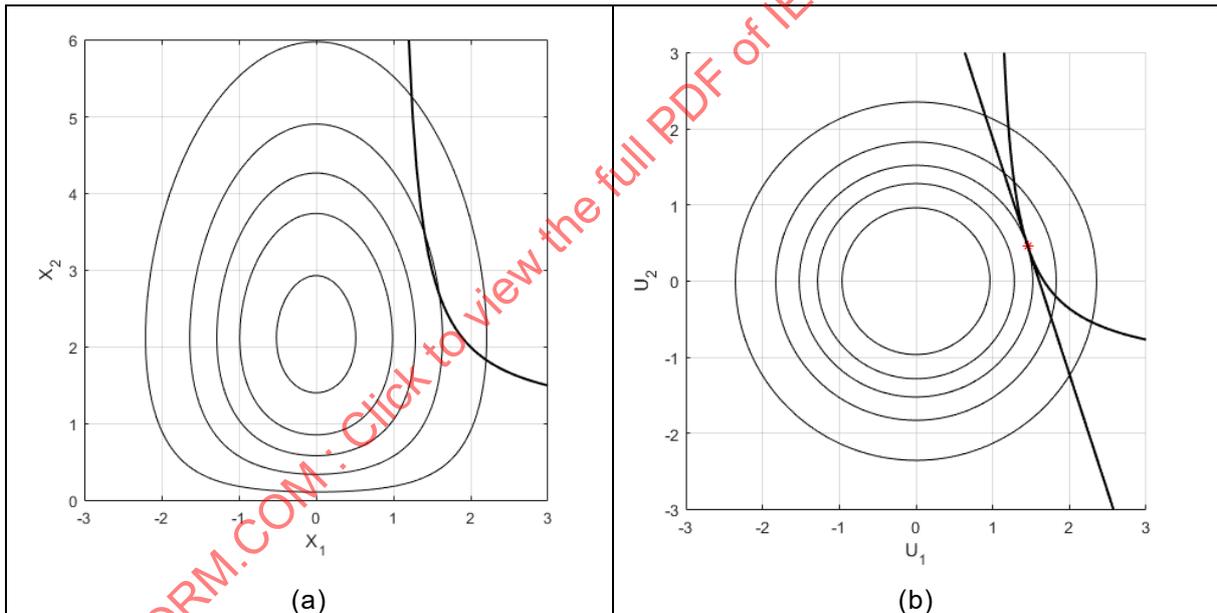
1113 where  $F_{X_i}$  is cumulative distribution of each random variable component  $X_i$  and  $\Phi^{-1}(\cdot)$  is the  
 1114 inverse normal cumulative distribution function.

1115 After the transformation, the probability integration becomes:

$$P_f = \int_{g(U)<0} \phi_U(\mathbf{u})d\mathbf{u} \tag{29}$$

1116 This integrand is simplified since  $\phi_U$  becomes the product of the standard normal probability  
 1117 density functions of  $u_i$  since in the new space the variables are independent.

1118 The second step is to approximate the integration boundary  $g(U) = 0$  by linearizing it (first order  
 1119 Taylor expansion) around the “most probable failure point” ( $\mathbf{u}^*$ ) which is the point that has the  
 1120 highest probability density at the hyper-surface defined by the limit state equation, see Figure 5  
 1121 for an illustration of a problem consisting of only two physical dimensions.



1122 **Figure 5 – Illustration of the FORM method for a simplified two-variable case: (a)**  
 1123 **Original physical space. (b) Change of variables through the Rosenblatt transformation**  
 1124 **and approximation of the integration boundary by its first order Taylor expansion at the**  
 1125 **most probable point.**

1126 It can be shown that under such approximations the reliability index  $\beta$  is equal to the norm of  
 1127 vector  $\mathbf{u}^*$ . The probability of failure can therefore be estimated based on (30), giving  $P_F \approx$   
 1128  $\Phi(-\beta)$ .

1129 Some examples of how to apply such methods to simplified problems relevant to wind turbine  
 1130 design are presented in Annex C.

### 1131 8.1.3 Accuracy requirements

1132 Due to the computational complexity, the calculated failure probability is an approximation to  
1133 the exact result. Two fundamental accuracy requirements are:

- 1134 • Overestimation of the reliability due to use of an approximative calculation method shall  
1135 be within limits generally accepted for the specific type of structure as stated on  
1136 structural safety standards and relevant national codes.
- 1137 • The overestimation of the reliability index due to the calculation method applied should  
1138 not exceed 5 % with respect to the target level.

1139 The accuracy of the reliability calculation method is linked to the sensitivity with respect to  
1140 structural dimensions and material properties in the resulting design. When using approximate  
1141 methods, this accuracy may be estimated by comparing the results with ones obtained with use  
1142 of simulations methods for a similar case. When using a simulation method, the accuracy of the  
1143 solution may be estimated on some conditions by computing the sensitivity of the result with  
1144 the number of simulations performed.

### 1145 8.1.4 Sensitivity analysis

1146 A sensitivity analysis shall be performed in the context of any probabilistic design exercise with  
1147 the objective of identifying which uncertainty considerations are contributing most to the  
1148 computed reliability.

1149 To perform such a study, the reliability method used should be capable of producing a sensitivity  
1150 analysis including importance factors for uncertain parameters.

1151 An example of how to perform a sensitivity analysis is given in C.1.6.

## 1152 8.2 Reliability-based method

1153 In a full reliability-based design the design parameters (i.e. geometric properties of a given  
1154 component) are themselves determined based on a reliability analysis. This means that loads  
1155 (actions), resistances (strength parameters) and models are modelled by probabilistic models  
1156 and design parameters of the component are determined to achieve the target failure  
1157 probability.

### 1158 8.2.1 Probability of failure for extreme design situations

1159 Annex C.1 illustrates the reliability assessment/design for extreme design situation based on a  
1160 simple modelling of the ultimate limit state. In some analysis it is not possible to develop an  
1161 analytical model such as the one represented in equation (72) in which case numerical models  
1162 may be used to build a mapping between load effect and stress/resistance. In such cases, it  
1163 should be ensured that any additional numerical uncertainty is captured in the factor  $X_{str}$ . More  
1164 complex cases where even such a mapping is not possible, direct use of numerical models for  
1165 evaluation of (72) can be used and the probability of failure computed through direct Monte-  
1166 Carlo simulations. It is noted that the computation complexity of setting up different models  
1167 covering the desired uncertainty space and running such models the required number of times  
1168 may prove to be prohibitive.

### 1169 8.2.2 Probability of failure for fatigue design situations

1170 Annex C.2 illustrates the reliability assessment for fatigue design situations based on a simple  
1171 damage accumulation model (Palmgren-Miner) with mean stress level. The example should be  
1172 considered just as an illustration of reliability-based fatigue analysis, not a recognized baseline  
1173 for general fatigue design.

1174 Modelling of fatigue resistance of materials can be generally divided in two main approaches:  
1175 damage summation and fracture mechanics (crack growth models).

#### 1176 **Damage based approaches**

1177 These can be further sub-divided corrected/normalized S-N diagrams and lifetime diagrams,  
1178 depending on the type of material and component failure mode under consideration. References  
1179 to recognized standards for the material/component type justifying the application of a particular  
1180 model should be provided (e.g. ISO 2394 or EN 1993-1-9) as long as also in accordance with  
1181 IEC 61400-1.

#### 1182 **Fracture mechanics approaches**

1183 Due to a general dependence of fatigue loads with atmospheric turbulence levels, the load cycle  
1184 history for wind turbines cannot be predicted in advance. Therefore, the use of fracture  
1185 mechanics approaches in the design phase are typically subject to a calibration of the method  
1186 against simpler damage accumulation models (such as the Palmgren-Miner model). On the  
1187 other hand, it may be possible or even necessary to use it as a verification of safe life and in  
1188 the planning of inspection intervals, see 8.2.3. Further guidance is provided in component  
1189 design standards such as IEC61400-8.

#### 1190 **8.2.3 Updating probability of failure using test or inspection data**

1191 Two distinct types of updating are considered here:

- 1192 • When knowledge of new information due to test, operational data or access to new  
1193 measurement or modelling databases allows one to update some of the probability  
1194 distributions composing the overall probabilistic model used in a particular investigation
- 1195 • When knowledge of a particular event (i.e. crack detection) is gained by realization of  
1196 inspections on an operating turbine

1197 For the first type of updating, Bayesian updating methods as described in Annex A.1 can be  
1198 used to combine new knowledge with the initial assumptions of the probabilistic model and  
1199 generate updated probability distribution for a particular variable of interest. Examples of such  
1200 application is updating structural properties of a particular material given tests of specific  
1201 batches (i.e. sampling of concrete) or updating uncertainties through use of site specific data  
1202 as discussed in Annex E.

1203 In the second case, both Bayesian methods (i.e. Bayesian updating, Bayesian networks) and  
1204 reliability-based inspection (RBI) methods can be used. RBI is based on Bayesian decision  
1205 theory, and it aims at minimizing the total expected cost of an inspection plan while considering  
1206 the expected costs of failure, inspection, and repair.

1207 When using methods such as RBI, it should be considered that inspections are error prone and  
1208 therefore have themselves a probability of correctly detecting a defect or event (i.e. crack of a  
1209 given size – for crack detections in particular, note that crack identification procedures are  
1210 limited in their accuracy due to coating, method of measurement, etc.). For updating failure  
1211 probabilities based on crack detection and propagation, the use of fracture mechanics is  
1212 necessary (see also (BS 7910 and IEC 61400-8).

1213 Note that the methods highlighted above are not exhaustive, and many probabilistic or statistical  
1214 methods are available to address a particular problem.

### 1215 **8.3 Semi-probabilistic method**

1216 As described in ISO2394, semi-probabilistic methods may be applied as an alternative to risk  
1217 and reliability-based decision making. Consequence class categorizations, design situations  
1218 and design equations are defined following the design basis requirements put forward in IEC  
1219 61400-1 and in accordance with clause 5 of this standard.

#### 1220 **8.3.1 Representative and characteristic values**

##### 1221 **Actions**

1222 Characteristic values for actions shall be defined according to the principles in ISO2394. In  
1223 particular, the characteristic value of variable actions for normal design situations is chosen to  
1224 be the 98% quantile of the annual maximum action effect, as intended by the calculations  
1225 indicated in IEC 61400-1.

##### 1226 **Resistance**

1227 Characteristic values for properties of materials shall be defined according to the principles in  
1228 ISO 2394. Typically, and according to IEC 61400-1, the characteristic value of the resistance  
1229 parameter is defined by the 5% quantile

##### 1230 **Uncertainties**

1231 The representative uncertainty levels indicated in Annex A are used and form an acceptable  
1232 baseline if one follows state-of-the-art industry practices and recognized practices established  
1233 by the related governing safety standards for structural design.

#### 1234 **8.3.2 Partial factor method for extreme and fatigue design situations**

1235 When using partial factors, the designer may either use the load and material factors present  
1236 in other standards in the IEC 61400 series or calibrate the factors to be used following the  
1237 principles in this technical specification. When calibrating partial factors, the designer shall  
1238 ensure that failure probabilities for the relevant failure modes are close to the target reliability  
1239 level defined in 5.

#### 1240 **8.3.3 Reliability-based calibration of partial safety factors**

1241 Re-calibration of safety factors may be based on justified revision of the representative  
1242 uncertainty levels or assumptions on the load effects or related event probabilities which define  
1243 a particular design case.

1244 In the case of re-calibration, first an updating of the probabilistic model governing the limit state  
1245 under study shall be made based on a suitable method such as the ones suggested in 8.2.3 or  
1246 Annex A. The new probabilistic model can then be used to estimate the partial safety factor  
1247 according to the method described in Annex C.

1248

1249

## 1250 **9 Site suitability analysis**

### 1251 **9.1 General approach and scope**

1252 Wind turbines are subjected to site-specific environmental and electrical conditions including  
1253 the influence of nearby turbines, which may affect their loading, durability and operation. It shall  
1254 be shown that the site-specific conditions do not compromise the structural integrity.

1255 This site suitability assessment can either be done using the semi-probabilistic approach  
1256 presented in IEC61400-1 or the reliability-based probabilistic approach hereby presented, as  
1257 defined in ISO 2394.

1258 The IEC61400-1 is taken as basis with regards to the definition of load cases and requirements  
1259 for the site suitability assessment.

1260 The principles presented here are applicable for the site suitability structural assessment of  
1261 onshore and offshore with turbines, as well as for the structural assessment of the lifetime  
1262 extension of installed wind turbines.

1263 This approach can be applied to wind turbines that had been designed using the probabilistic  
1264 approach described in previous chapters of this Technical Specification; or designed using the  
1265 semi-probabilistic approach based on partial safety factors in IEC 61400-1. In the latter case  
1266 the design capacity in terms of the quantile of the strength distribution and the partial safety  
1267 factor shall be available for the considered limit states. The quantile of the load distribution may  
1268 be derived from frequency distributions of environmental parameters that are characteristic of  
1269 long-term conditions on site or from time series observations acquired on site adjusted to reflect  
1270 conditions prevailing over the long term.

1271 The site suitability assessment based on a probabilistic approach focuses on assessing the  
1272 relative variation of the structural reliability level respect to the design assumptions, when site  
1273 specific conditions are considered, and accounting for different sources of uncertainties  
1274 associated to the site assessment data and models.

1275 The probabilistic approach can be applied to perform a complete site suitability assessment or  
1276 just the assessment of some limit states, failure modes, or load cases (FLS, ULS, Accidental...)  
1277 All other limit states can be assessed using the deterministic approach of IEC61400-1. If a  
1278 probabilistic approach was used for the design and the site assessment is made according to  
1279 the deterministic approach of IEC 61400-1 based on load calculations, then the characteristic  
1280 strength for the considered limit state as defined in IEC 61400-1 should be provided from the  
1281 probabilistic design. Similarly, if the site assessment is performed by reference to wind data  
1282 according to IEC 61400-1 then the characteristic wind conditions for the considered limit state  
1283 as defined in IEC 61400-1 should be provided from the probabilistic design.

1284 If the site suitability assessment based on a probabilistic approach is performed by using  
1285 simplified loads or resistance models, an additional uncertainty factor and/or bias shall be  
1286 included in the models to account for that simplification. For instance, if a generic resistance  
1287 model is used to model the load-bearing capacity of the structural component without further  
1288 details about the actual strength characteristics of the component. If there is no information  
1289 about the actual strength of the component, it shall be assumed that the component is designed  
1290 to the limit in the design wind conditions.

1291 The results from this analysis can be used to make decisions regarding site suitability of wind  
1292 turbines, instead of a deterministic approach, as long as the resulting reliability level is kept  
1293 within and acceptable target values defined in 5.  
1294

## 1295 **9.2 Reliability models for site suitability analysis**

1296 Different Limit State Equations can be defined for the assessment of different limit states  
1297 relevant for the site assessment, in accordance with other parts of this Technical Specification.  
1298 As defined in 9.1, the limit states evaluated with the probabilistic approach can cover all or part  
1299 of the load cases defined in IEC61400-1.

1300 As described in 7 the limit state function usually has two parts, one representing the resistance  
1301 or load-bearing capacity (R), and other representing the load effects (L).

1302 For the site suitability assessment special attention should be put on those parts of the limit  
1303 state equations that are more dependent on site-specific conditions or site suitability data,  
1304 methods and tools with respect to the design assumptions, such as:

- 1305 – Wind conditions and related uncertainties.
- 1306 – Computational models to estimate structural loads for site specific conditions, especially if  
1307 they are different to the ones used in the design (aeroelastic simulations, metamodels,  
1308 surface response, regression models...).
- 1309 – Resistance models to estimate load-bearing capacity, especially if they are different to the  
1310 ones used in the design (Damage models, Palmgren-Miner rule...).
- 1311 – Considerations about fatigue assessment.
  - 1312 – Reliability models may be time-variant or time-invariant, to consider eventual effects that  
1313 may change along time.
  - 1314 – Reliability models may be used to assess reliability at the end of the turbine lifetime or  
1315 at any year during the total lifetime
  - 1316 – The reliability models may also include the influence of defining decision rules along  
1317 turbine lifetime based on inspection, monitoring and maintenance plans.
- 1318 – Probability of the site-specific events. If the limit state equation is associated to an event  
1319 whose recurrence period is site dependent, the total probability of failure shall account for  
1320 the probability of that event.

1321

1322

1323 **9.2.1 Loads models for site suitability assessment**

1324 The loads model to be used for a probabilistic approach of a site-suitability assessment shall  
 1325 represent the dependency of the structural loads respect to the environmental conditions. Those  
 1326 loads models shall include stochastic variables accounting for the uncertainties in the  
 1327 environmental parameters (wind, marine), and the uncertainties in the methods to estimate wind  
 1328 turbine loads based on the site-specific conditions.

1329 Regarding the uncertainties related to site suitability assessment see 9.3.

1330 For the failure modes selected for the probabilistic assessment, limit state equations should be  
 1331 formulated based on the deterministic design equation, representing variables by their  
 1332 probability distributions, instead of using characteristic values and partial safety factors.  
 1333 Uncertainties related to external conditions, load assessment, and resistance (as described in  
 1334 chapter 6) should be included either directly, where the input variable is represented directly as  
 1335 a random variable in the limit state equation (see section a) below); or indirectly, where the  
 1336 effect of uncertainty on one or more variables is represented as a model uncertainty multiplied  
 1337 on the load effect in the limit state equation (see section b) below). A combination of both  
 1338 approaches is also possible.

- 1339 a) If the uncertainty related to the external conditions is included as random variables in  
 1340 the limit state equation

$$LOAD = X_{model} X_{..} f(W_{density}, W_{shear}, W_{turbulence}, \dots) \quad (30)$$

1341 *X* are random variables accounting for uncertainties not related to external conditions  
 1342 (aeroelastic model, material properties, loads application, etc).

1343 *f* is the loads model used to obtain the wind turbine loads based on wind or marine  
 1344 conditions, such as aeroelastic simulations, metamodels, surface response, regression  
 1345 models or others.

1346 *W* are random variables representing the different environmental parameters relevant  
 1347 for the loads (air density, wind shear, turbulence intensity, etc). They can be defined  
 1348 either by analytical formulation or Monte Carlo simulation.

1349 In this case, a hierarchical modelling (see ISO 2394) is recommended to model the  
 1350 uncertainty on wind or marine conditions. With this approach each of the environmental  
 1351 variables can be defined as a function of several variables, each one representing a  
 1352 specific type of variability:

$$W_{ijk} = f(W_i, W_{ij}, W_{ijk}) \quad (31)$$

1353 The random variable may also be defined as a result of several random variables  
 1354 accounting for different sources of uncertainties (physical, measurement, statistical or  
 1355 model):

$$W = A + B W_{physical} W_{measurement} W_{statistical} W_{model} \quad (32)$$

- 1356 b) If the uncertainty related to the external conditions is included as random variables that  
 1357 multiply the load effect at the nominal values of the external conditions

- 1358 c)

$$LOAD = X_{\text{model}} X_{\dots} X_{\text{wind meas}} X_{\text{wind stat}} X_{\text{wind model}} f(\rho_{\text{nom}}, \sigma_{1 \text{ nom}}, \alpha_{\text{nom}}, \dots) \quad (33)$$

1359  $X$  are the stochastic variables accounting for all sources of uncertainties. Such as  
 1360 general measurement uncertainty, statistical uncertainty and model uncertainty, Those  
 1361 include not only uncertainty in environmental parameters, but any other uncertainty

1362  $f$  is the loads model used to obtain the wind turbine loads based on the nominal value  
 1363 of the different wind or marine parameters (air density, wind shear, turbulence intensity,  
 1364 etc).

1365 If the approach b) is used, the stochastic variables  $X$  shall be properly calibrated based on the  
 1366 uncertainty in environmental parameters. This can be done using approach a) or other methods.

1367 A different loads model  $f$  shall be used for different load case and load effect of interest if  
 1368 required. Some of the stochastic variables accounting for other uncertainties may also depend  
 1369 on the load case and load effect.

1370 The propagation of the uncertainties of environmental conditions through the loads model shall  
 1371 be done applying recognized techniques as described in 6.3.2.  
 1372

## 1373 **9.2.2 Resistance model for site suitability assessment**

1374 The resistance models for probabilistic design are generally described in 6. However, the  
 1375 assessment of structural integrity for site-specific conditions may be based on different, usually  
 1376 simplified, resistance models.

1377 If the resistance or loads model used for site suitability assessment is different to the one used  
 1378 in the design, that should be accounted for with appropriate uncertainties. The eventual change  
 1379 of resistance along turbine lifetime should also be considered if relevant using appropriate time  
 1380 variant reliability analysis.

1381 Site suitability assessment can be performed either using complete detailed information of  
 1382 turbine structural design or using only limited information. An absolute or a relative approach  
 1383 may be followed to perform a probabilistic site suitability assessment.

### 1384 **9.2.2.1 Absolute approach**

1385 In an absolute approach loads can be derived either by the aero-elastic model used in design  
 1386 or using alternative, simplified loads models (see clause 9.2.1), in which case the corresponding  
 1387 uncertainty of the loads model should be accounted for, along with other assumptions on  
 1388 uncertainties of the load side (apart from the uncertainties on wind climate, which are obviously  
 1389 site specific) that were used in the design, e.g. uncertainty in aero-elastic modelling, uncertainty  
 1390 in transforming loads into stresses, ...

1391 Uncertainties in the wind climate are modelled site specifically.

1392 On the resistance side uncertainty modelling from the design is used, based on the known  
 1393 material and geometry properties of the components under consideration.

1394 **9.2.2.2 Relative approach**

1395 A relative approach is a simplified approach that can be applied, for instance, if the design  
 1396 assumptions (in particular those regarding the probabilistic design) are unknown. The following  
 1397 steps are undertaken.

- 1398 1. A generic model will be used in the aero-elastic calculations. e.g. based on simplified  
 1399 turbine data or reverse-engineered to match the information/data available at this point  
 1400 (e.g. power curve, thrust curve, eigenfrequencies, foundation loads, ...). Since this  
 1401 model is deviating from the complete detailed aeroelastic model, it has some uncertainty  
 1402 associated that needs to be estimated / assessed. For the remaining uncertainties on  
 1403 the load side (other than the wind climate parameters) assumptions shall be justified  
 1404 (e.g. for exposure or loads-to-stress-transforms). See Clause 6 and Annex A for  
 1405 guidance on representative values of uncertainties
- 1406 2. Define assumptions on design uncertainties (in compliance with IEC 61400-1 and this  
 1407 technical specification) for loads.
- 1408 3. On the resistance side reasonable assumptions shall be made for uncertainties for  
 1409 material, damage accumulation or other failure modes (e.g. buckling).
- 1410 4. Calibrate a design parameter to reach the target component reliability under design  
 1411 assumptions; check result for plausibility.
- 1412 5. Uncertainties in the wind climate are modelled site specifically.
- 1413 6. Calculate site specific reliability with assumptions and  $z$  parameter from previous steps.

1414 Annex F includes an example of the relative approach to site suitability assessment.

1415 **9.2.3 Site-specific exposure events**

1416 The structural reliability assessment for site specific conditions may also account for the  
 1417 probability of exposure events whose intensity and/or probability of occurrence is site  
 1418 dependent, since it will affect the final probability of failure. The exposure events represent all  
 1419 events which can cause damage or otherwise affect the performance indicators of the wind  
 1420 turbine structure

1421 Exposure events for wind turbines can be classified as fault events or wind events

1422 **9.2.3.1 Fault events**

1423 Fault events can either be internal turbine faults (e.g. turbine control system fault) or external  
 1424 fault events. This is of special relevance for the failure load cases defined in IEC 61400-1.  
 1425 Some examples of fault events are:

- 1426 – External electrical events, such as loss of electrical network, voltage drops, ...
- 1427 – Turbine control system faults, considering that the probability of some turbine faults may  
 1428 depend on site-specific conditions (e.g. a site with severe dust, corrosion or humidity  
 1429 conditions may increase the faults of some actuation or electrical systems)

1430 The probabilistic analysis of fault events, as for design situation 2) and load cases DLC6.2 and  
 1431 DLC7.1 of IEC 61400-1, can be done based on failure rates, so that the rate of structural failure  
 1432 due to fault events can be obtained as:

$$\lambda_F = \lambda_E P(L > R|E) \tag{34}$$

1433 where

1434  $\lambda_F$  Failure rate obtained as number of turbine failures per year.

1435  $\lambda_E$  Number of events per year.

1436  $P(L > R|E)$  Probability of structural failure per turbine per year conditioned on the given  
 1437 event

### 1438 9.2.3.2 Wind conditions

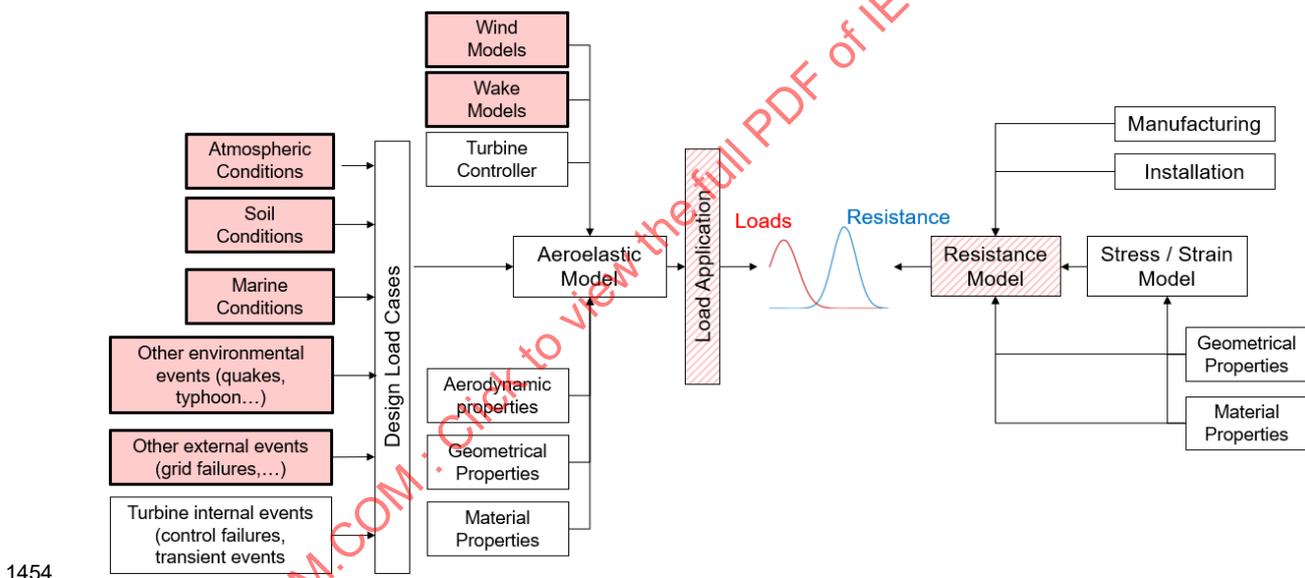
1439 Wind events are those where the turbine is not subjected to faults (internal nor external) and  
 1440 the loads are driven by wind conditions

1441 The site-specific wind conditions are assessed based on the analysis of deterministic wind field  
 1442 events and turbulent models, according to IEC61400-1

1443 Site-specific wind data can be used to define stochastic models for deterministic wind field or  
 1444 turbulent wind conditions, including also models for wind speed, turbulence intensity, air  
 1445 density, wind shear and flow inclination. If the turbine was designed using a stochastic model  
 1446 for deterministic wind field event or turbulent wind conditions different to the ones described in  
 1447 6.2.2.2, the assumptions for such models should be validated for the specific site where the  
 1448 turbine suitability is assessed.

### 1449 9.3 Site specific uncertainty modelling

1450 The general description and requirements for representation and modelling of uncertainty for  
 1451 probabilistic design of wind turbines are described in 6. Figure 6 highlights the more relevant  
 1452 uncertainties related to site suitability assessment. Uncertainty modelling can either include the  
 1453 variability, usually expressed as coefficient of variation or standard deviation, and/or a bias



1454

1455 **Figure 6 – Highlight of relevant uncertainties related to site suitability assessment.**

- 1456 – Physical and epistemic uncertainties of atmospheric conditions (refer to IEC61400-1 for a  
 1457 more detailed description of atmospheric parameters):
- 1458 – Extreme 10min average wind speed
  - 1459 – Wind speed probability density function
  - 1460 – Wind speed standard deviation from ambient turbulence
  - 1461 – Extreme ambient wind speed standard deviation
  - 1462 – Flow inclination
  - 1463 – Wind shear
  - 1464 – Air density
- 1465 – Physical and epistemic uncertainties of marine conditions, defined in IEC61400-3, such as:

- 1466 – Wave spectrum (significant wave height, wave periods, etc.)
  - 1467 – Separation of swell and wind driven waves
  - 1468 – Wind/wave misalignment
  - 1469 – Currents
  - 1470 – Tide and storm surge
  - 1471 – Extreme wave and associated wave periods
  - 1472 – Soil conditions:
    - 1473 – Geotechnical conditions (p-y curves)
    - 1474 – Seabed variation (offshore)
    - 1475 – Scour development (offshore)
  - 1476 – Wind and wake models
    - 1477 – Models for turbulent wind simulation
    - 1478 – Models to account for the wake effect on the wind flow
  - 1479 – Uncertainty on external events (type, intensity, recurrence period...)
    - 1480 – Grid events (grid drops, network outages, ...)
    - 1481 – Other environmental events (earthquakes, icing...)
    - 1482 – Turbine operational transients (shutdowns, start-up...)
    - 1483 – Turbine failures in control system, electrical components
  - 1484 – Statistical and Model uncertainty of loads estimations
    - 1485 – Wind turbine characteristics (geometry, structural properties, aerodynamic properties)
    - 1486 – Foundation characteristics (foundation and terrain)
    - 1487 – Loads models used to estimate the site-specific loads based on wind conditions (full aeroelastic simulations, surrogate models, interpolation models, response surface methods, neural networks ...).
    - 1488
    - 1489
    - 1490 – Uncertainties on models for structural dynamics, aerodynamics, sensors, actuators
    - 1491 – Statistical uncertainty due to the limited amount of simulations
- 1492 Site suitability assessment is usually based on simplified loads and/or resistance models, in  
 1493 which case it should be considered the uncertainties due to consider simplified load effects  
 1494 models (e.g.- Damage equivalent Load) instead of more detailed load indicators (e.g.- complete  
 1495 Markov matrices); and the uncertainty in the resistance models used to determine structural  
 1496 stress based on load effects. See 9.3 for site specific uncertainty modelling and quantification
- 1497 The uncertainties in the site-specific atmospheric conditions used for site suitability assessment  
 1498 shall be accounted for. Main sources of such uncertainties are described below
- 1499 – Physical uncertainty of atmospheric conditions: It is the inherent uncertainty related  
 1500 to the natural randomness of the wind characteristics, for example the uncertainty  
 1501 in the wind speed distribution due to the year-to-year variation of climatic conditions.
  - 1502 – Measurement uncertainties of the environmental conditions derived from different  
 1503 sources, for example:
    - 1504 – The operational characteristics of the wind sensor device, due to the  
 1505 classification or type of instrument. This covers the sensitivity of accuracy of a  
 1506 type of wind sensor to environmental variables and other operational conditions
    - 1507 – The calibration of the individual unit used in the specific measurement campaign
    - 1508 – Mounting effects. For anemometers mounted on meteorological masts this is due  
 1509 to the interference of the mast or the boom on the actual flow measured by the

- 1510 anemometer. For remote sensor devices it is the uncertainty of non-ideal  
1511 levelling of the device.
- 1512 – Configuration, or the proper maintenance, installation and operation of  
1513 measurement devices during a specific measurement campaign.
  - 1514 – The influence from the terrain.
  - 1515 – Amount of measured data: It is statistical uncertainty due to the limited amount of  
1516 data.
  - 1517 – Long-term estimations: It is the model uncertainty of the methods used to predict the  
1518 long-term characteristics of the wind distribution based on the data available. (e.g.-  
1519 Measure-Correlate-Predict methods); or to predict the extreme values of the wind  
1520 characteristics (e.g.- Gumbel method, Method of Independent Storms,...). It is also  
1521 related to the amount of data available.
  - 1522 – Vertical extrapolation uncertainty: It is the statistical uncertainty due to the limited  
1523 number of heights where wind data is available, that may be especially relevant for  
1524 estimation of wind shear characteristics
  - 1525 – Wind modelling: It is the model uncertainty of the wind flow models used to estimate  
1526 the wind conditions at different locations of the site based on the data available at  
1527 the measurement position. It depends on several factors, such as:
    - 1528 – Wind flow model: It is the model uncertainty of the computational fluid dynamic  
1529 model itself
    - 1530 – Mesoscale wind flow model: It is the uncertainty of the wind flow models based  
1531 on mesoscale data, in opposition to flow models based on wind data measured  
1532 directly at the site.
    - 1533 – Terrain map quality: it is the statistical uncertainty due to the limited information  
1534 of terrain topography, depending on the quality of the map to represent  
1535 accurately such topography based on the contour lines.
    - 1536 – Wind shear complexity: It is the uncertainty in the characterization of wind shear  
1537 depending on how well the terrain roughness is characterized and the stability  
1538 effects of atmosphere.
    - 1539 – Terrain complexity: It is the uncertainty of the wind modelling due to the  
1540 characteristics of terrain topography
    - 1541 – Horizontal extrapolation: It is the model uncertainty to predict the wind  
1542 characteristics far from the measurement point.
    - 1543 – Wake models: It is the uncertainty of the models used to predict the  
1544 characteristics of the wind in the wakes.
    - 1545 – Turbulence models used to generate the synthetic turbulent wind field for  
1546 aeroelastic simulations

1547 It may not be necessary to model all uncertainties listed above explicitly. Instead, related  
1548 uncertainties can be combined into a single stochastic variable, and some uncertainties can be  
1549 covered by general model uncertainties related to e.g., turbulent wind field generation and/or  
1550 loads simulation.

1551 Annex G provides some qualitative examples of best- and worst-case scenarios for the different  
1552 sources of uncertainties in atmospheric conditions.

1553 Sources of uncertainty in the marine conditions include:

- 1554 – Wave conditions: It is the uncertainty related to the measurement and/or numerical  
1555 hindcasting techniques used to derive the joint probability distribution of mean wind  
1556 speed, wind direction, wave direction, significant wave height and peak spectral period  
1557 in relation to:
  - 1558 – Normal sea states

- 1559 – Severe sea states
- 1560 – Extreme sea states
- 1561 – Sea currents: It is the uncertainty related to the derivation of near- and sub-surface
- 1562 currents in relation to:
  - 1563 – Normal current models
  - 1564 – Extreme current models
- 1565 – Water levels: It is the uncertainty related to the measurement and/or estimation of the
- 1566 Normal water level range as well as the long-term joint probability distribution of the
- 1567 extreme water level range
- 1568 – Marine growth on the substructure or mooring lines of floating turbines
- 1569 – Soil conditions: It is the uncertainty related to the interpretation of data from, e.g. Cone
- 1570 Penetration Test, and borehole logs, seabed variations and scour development
- 1571 – Depth or seabed level

1572 Other possible sources of uncertainties should be considered when relevant for the site  
 1573 suitability assessment, such:

- 1574 – Uncertainty in the characterization of other environmental events, like typhoons,
- 1575 earthquakes, sea ice, tides, currents, icing
- 1576 – Uncertainty in the soil conditions.
- 1577 – Uncertainty in strength characteristics of the material due to site specific environmental
- 1578 conditions, like the effect of corrosion or extreme low temperatures.
- 1579 – Uncertainty in the knowledge of some other exposure events.
- 1580 – Uncertainty in the Loads application models. It is the uncertainty in aeroelastic response
- 1581 loads model used to estimate the site-specific wind turbine loads based on the wind
- 1582 conditions, especially if they are different to the loads models used for the design.

1583 If the strength characteristics of the wind turbine can be assumed to be invariant to the site  
 1584 conditions, only the uncertainties on the loads part need to be modified according the site-  
 1585 specific conditions.

1586 For offshore wind turbines, some parts of the structure are usually site-specific designs, such  
 1587 as the substructure in fixed turbines; or the floating platforms, mooring lines and anchoring  
 1588 systems in floating turbines. In those cases, it may be especially relevant to consider site-  
 1589 specific uncertainties also in the structural and geometrical characteristics of such parts.

1590 A sensitivity analysis of the different sources of uncertainties should be done to identify the  
 1591 most relevant uncertainties sources to include in the reliability model.

1592 **9.3.1 Quantification of site-specific uncertainties**

1593 The quantification of site-specific uncertainties shall be based on the methods described in 6.

1594 Different approaches are used to quantify the different types of uncertainties of a specific site:

1595 Physical uncertainties of the environmental conditions can be assessed based on sites with  
 1596 similar climatic characteristics.

1597 Measurement uncertainties of the environmental parameters can be defined by the uncertainty  
 1598 of the calibration of the measurement devices and by analysis of a similar measurement set up  
 1599 (same type of anemometer or wind sensing device) installed in a similar way in representative  
 1600 operating conditions.

1601 Statistical uncertainties of the environmental parameters can be defined by analysis of large  
1602 datasets of data on sites with similar climatic characteristics.

1603 Model uncertainties of the wind flow model can be defined based on the comparison with more  
1604 advanced models or flow measurements in sites with similar characteristics (terrain complexity,  
1605 surface roughness, atmospheric stability, etc.).

1606 Model uncertainties in the loads and resistance models used for site suitability assessment can  
1607 be defined based on the comparison with more advanced validated simulation models or with  
1608 measurements in real turbines.

1609 Annex G provides some qualitative examples of uncertainty scenarios of epistemic  
1610 uncertainties in the wind assessment as well as some reference values for uncertainties in  
1611 relevant wind parameters in a normal scenario.

1612

#### 1613 **9.4 Reliability assessment**

1614 The reliability assessment for the site suitability analysis can either be performed by  
1615 determination of the probability of failure based on detailed load and strength models for site-  
1616 specific conditions representing the aerodynamic, structural geometrical and material  
1617 properties of the turbine components, or by determination of the probability of failure for the  
1618 site conditions based on a simplified model relative to that for the design conditions. In the latter  
1619 case the reliability model should be calibrated to match the expected target design reliability  
1620 when the design assumptions are used e.g.- by means of adjustment of a design parameter  $z$   
1621 in the resistance model of the limit state function

1622 The reliability assessment shall be done using the methods described in 8, showing that the  
1623 resulting reliability level meets the acceptable target values defined in 5.2.

1624

1625  
1626  
1627  
1628

## Annex A (informative)

### Uncertainty quantification

1629 Uncertainty quantification is here understood as the estimation of distribution types and distribution  
1630 parameters for variables modelling uncertainties. Generally, it is necessary to include statistical  
1631 uncertainties in the assessment. This annex describes the application of Bayesian methods and the  
1632 Maximum likelihood method for this purpose.

#### 1633 A.1 Bayesian methods

1634 Bayesian methods enable the combination of new data with existing information, and it enables hieratical  
1635 modelling of uncertainties. The theoretical description is generic and can be applied to all hierarchies  
1636 and distribution types.

1637 Bayes rule states that the posterior distribution  $P(\theta|\varepsilon)$  of a variable is proportional to the product of the  
1638 prior distribution  $P(\theta)$  and the likelihood function  $P(\varepsilon|\theta)$ :

$$P(\theta|\varepsilon) \propto P(\theta) P(\varepsilon|\theta) \quad (35)$$

1639 Here  $\theta$  is a variable, and  $\varepsilon$  is the data or *evidence* available for updating/estimating the distribution for  
1640  $\theta$ . For example,  $\theta$  can be a parameter in a distribution for a variable  $X$ . The updated distribution for  $X$ ,  
1641 considering the data and prior information, is called the predictive distribution  $P(X|\varepsilon)$ , and it includes  
1642 both the variation of  $X$  around the mean value, and the variation caused by statistical uncertainty on the  
1643 parameters.

1644 While Bayes rule holds for all distribution types, closed form solutions can only be found for specific  
1645 combinations of prior and likelihood functions; the so-called conjugate distributions. An example is the  
1646 normal distribution. If both the prior and likelihood distributions are normal distributions, the posterior  
1647 distribution is also a normal distribution, and a closed form solution can be found. For hieratical models  
1648 with normal distributions, where other variables are described as linear combinations of normal  
1649 distributions, exact solutions can be found for the posterior distributions. For discrete distributions, exact  
1650 solutions can also be derived. However, for arbitrary choices of continuous distributions, exact solutions  
1651 cannot be found for the posterior distributions. Instead sampling based methods can be applied, or the  
1652 continuous parameters can be discretized. For hieratical models, graphical models such as Bayesian  
1653 networks are especially suitable.

1654 When comparing Bayesian methods to other methods for estimation of parameters, Bayesian methods  
1655 have the advantage, that existing information can be accounted for in the prior. However, Bayesian  
1656 methods can also be used when no prior information is available, by using a non-informative prior: e.g.  
1657 a normal distribution with a very high coefficient of variation.

#### 1658 A.1.1 Closed form solutions for parameter estimation

1659 Closed form solutions exist for the predictive distribution of  $X$  for (among others) the following cases,  
1660 where the population of  $X$  follows a normal distribution with unknown mean and known/unknown  
1661 standard deviation  $\sigma$ .

- 1662 • Known population standard deviation (Figure A.1)
  - 1663 ○ No prior information on the mean
  - 1664 ○ Prior information on the mean
- 1665 • Unknown population standard deviation (Figure A.2)
  - 1666 ○ No prior information on the mean and/or standard deviation
  - 1667 ○ Prior information on the mean and/or standard deviation



1668

1669 **Figure A.1 – Graphical representation of the structure for estimation of (a) the mean**  
 1670 **value of X when the population variance is known and (b) the mean value and the**  
 1671 **variance of X.**

1672 The predictive distribution of  $X$  is estimated using the prior information (if any) and a sample with sample  
 1673 size  $n$ , sample mean  $m$ , and sample standard deviation  $s$ :

$$m = \frac{1}{n} \sum_{i=1}^n x_i \quad (36)$$

$$s = \sqrt{\frac{1}{n-1} (x_i - m)^2} \quad (37)$$

1674 **Known population standard deviation, no prior information**

1675 The predictive distribution for  $X$  is a normal distribution:

$$X^p = m + Z \cdot \sigma \sqrt{1 + \frac{1}{n}} \quad (38)$$

1676 where  $Z$  follows a standard normal distribution. Note that for a large sample size  $n$ ,  $\sqrt{1 + \frac{1}{n}} \approx 1$ , whereby  
 1677  $X$  asymptotically approaches a normal distribution with mean and standard deviation equal to the sample  
 1678 values  $m$  and  $s$ .

1679 **Known population standard deviation, prior information**

1680 Prior information on the mean of  $X$ : normal distribution with sample mean  $m'$  and size  $n'$ . The predictive  
 1681 distribution for  $X$  becomes a normal distribution:

$$X'' = m'' + Z \cdot \sigma \sqrt{1 + \frac{1}{n''}} \quad (39)$$

1682 where

- 1683 •  $Z$  follows a standard normal distribution.
- 1684 •  $n'' = n' + n$
- 1685 •  $m'' = \frac{m'n' + mn}{n''}$

1686 **Unknown population standard deviation, no prior information**

1687 The predictive distribution for  $X$  is a Student's  $t$  distribution:

$$X'' = m + T_{n-1} s \sqrt{1 + \frac{1}{n}} \tag{40}$$

1688 where  $T_{n-1}$  follows a Student's t distribution with n-1 degrees of freedom. Note that for a large sample  
 1689 size  $n$ , the Student's t distribution approximates a normal distribution and  $\sqrt{1 + \frac{1}{n}} \approx 1$ , whereby  $X$   
 1690 asymptotically approaches a normal distribution with mean and standard deviation equal to the sample  
 1691 values  $m$  and  $s$ .

1692 **Unknown population standard deviation, prior information**

1693 The prior information on the mean and standard deviation of  $X$  is given by parameters  $m', \nu', s', n'$ . The  
 1694 prior for the mean is a normal distribution with mean  $E[\mu] = m'$  and standard deviation  $\sigma/\sqrt{n'}$   
 1695 (corresponding to prior information originating from a sample with size  $n'$ ). To obtain a conjugate prior  
 1696 for the standard deviation, the inverse of the squared standard deviation has a gamma distribution as  
 1697 prior, defined by the prior expected value of the standard deviation  $E[\sigma] = s'$  and the prior degrees of  
 1698 freedom  $\nu'$ . The prior degrees of freedom is related to the coefficient of variation of the standard deviation  
 1699 as follows:  $COV[\sigma] = 1/\sqrt{2\nu'}$

1700 The predictive distribution for  $X$  is a Student's t distribution:

$$X'' = m'' + T_{\nu''} s'' \sqrt{1 + \frac{1}{n''}} \tag{41}$$

1701 where

- 1702 •  $T_{\nu''}$  follows a Student's t distribution with  $\nu''$  degrees of freedom
- 1703 •  $\nu = n - 1$
- 1704 •  $\nu'' = \nu' + \nu + 1$  for  $n' \geq 1$  and  $\nu'' = \nu' + \nu$  for  $n' = 0$
- 1705 •  $n'' = n' + n$
- 1706 •  $m'' = \frac{m'n' + mn}{n''}$
- 1707 •  $s''^2 = (\nu' s'^2 + n' m'^2 + \nu s^2 + n m^2 - n'' m''^2) / \nu''$

1708 **Lognormal variable**

1709 If a variable  $X$  follows a lognormal distribution,  $Y = \ln X$  follows a normal distribution. Therefore, the  
 1710 same approaches as above can be used for lognormal distributions, by making the inference on the  
 1711 logarithm of the variable.

1712 For example, for the case with unknown population standard deviation and no prior information:

$$\ln X = m_{\ln X} + T_{n-1} s_{\ln X} \sqrt{1 + \frac{1}{n}} \tag{42}$$

1713 where

- 1714  $T_{n-1}$  follows a Student's t distribution with n-1 degrees of freedom
- 1715  $m_{\ln X}$  is the sample mean of  $\ln(X)$
- 1716  $s_{\ln X}$  is the sample standard deviation of  $\ln(X)$

1717

1718 The predictive distribution for  $X$  is then given by:

$$X = \exp\left(m_{\ln X} + T_{n-1} s_{\ln X} \sqrt{1 + \frac{1}{n}}\right) = \exp(m_{\ln X}) \exp\left(T_{n-1} s_{\ln X} \sqrt{1 + \frac{1}{n}}\right) \quad (43)$$

### 1719 A.1.2 Exact inference for continuous parameters

1720 Exact inference can be performed for hierarchical models of normal distributions, where the top nodes  
 1721 follow normal distributions (prior distributions with given mean and variance), and the conditional  
 1722 probability distribution of the other nodes are normal distributions with mean values written as a linear  
 1723 combination of other normal distributed variables, and with known standard deviation. For variables that  
 1724 can be written as a product of lognormal distributed variables, the logarithmic transformation can be  
 1725 used, whereby the same approach can be used.

### 1726 A.1.3 Sampling-based inference

1727 For models with arbitrary continuous distribution types and relationships between parameters, sampling  
 1728 based methods such as Markov Chain Monte Carlo (MCMC) methods can be used. Top nodes are  
 1729 described by their prior probability distributions, and other nodes can be represented by deterministic  
 1730 functional relationships or by density functions, where other nodes can enter as distribution parameters.  
 1731 Nodes described by functional relationships are referred to as logic nodes, whereas the other nodes are  
 1732 stochastic nodes. In a Markov Chain, the joint distribution of the simulated sample approximates the  
 1733 true joint distribution, when samples from the run-in period are discarded, and a sufficient number of  
 1734 samples is obtained, see (Gilks et al. (1996).

### 1735 A.1.4 Exact inference for discretized parameters

1736 For hierarchical models with discrete distributions, where all distributions are given as (conditional)  
 1737 probability distributions, efficient algorithms exist for exact inference. The same method can be used for  
 1738 continuous distributions, by first discretizing the variables. Functional relationships can be approximated  
 1739 by conditional probability distributions.

## 1740 A.2 Maximum likelihood

1741 An often used method for parameter estimation is the Maximum Likelihood method. Here, distribution  
 1742 parameters are estimated such that the probability of receiving the sample is maximized. For some  
 1743 distribution types, analytical closed form solutions exist for the maximum likelihood estimate of the  
 1744 parameters. For other distributions, optimization algorithms can be used to estimate the parameters,  
 1745 based on a sample. The statistical uncertainty (standard deviations and correlation coefficients) related  
 1746 to the estimated parameters can be estimated based on the hessian matrix (consisting of the second  
 1747 derivatives of the loglikelihood function in the point of the maximum likelihood estimate).

1748 The likelihood function is the product of the probability density function  $f_X(x; \theta)$  evaluated in the  $n$  sample  
 1749 points, as function of distribution parameters  $\theta$ :

$$L(\theta) = \prod_{i=1}^n f_X(x_i; \theta) \quad (44)$$

1750 To ease the computations for analytical solutions and to avoid numerical underflow for numerical  
 1751 calculations, the loglikelihood function is used. When taking the natural logarithm of the likelihood  
 1752 function, the loglikelihood function is obtained:

$$LL(\theta) = \sum_{i=1}^n \ln(f_X(x_i; \theta)) \quad (45)$$

1753 The maximum likelihood estimate is found as the parameters maximizing  $LL(\theta)$  (and thereby also  $L(\theta)$ ).  
 1754 This can be done using numerical optimization algorithms or analytically from  $j$  equations:

$$\frac{\partial LL(\theta)}{\partial \theta_j} = 0 \tag{46}$$

1755 The hessian matrix for three parameters  $\theta_1, \theta_2, \theta_3$  is given by:

$$H = \begin{bmatrix} \frac{\partial^2 LL(\theta)}{\partial \theta_1^2} & \frac{\partial^2 LL(\theta)}{\partial \theta_1 \partial \theta_2} & \frac{\partial^2 LL(\theta)}{\partial \theta_1 \partial \theta_3} \\ \frac{\partial^2 LL(\theta)}{\partial \theta_1 \partial \theta_2} & \frac{\partial^2 LL(\theta)}{\partial \theta_2^2} & \frac{\partial^2 LL(\theta)}{\partial \theta_2 \partial \theta_3} \\ \frac{\partial^2 LL(\theta)}{\partial \theta_1 \partial \theta_3} & \frac{\partial^2 LL(\theta)}{\partial \theta_2 \partial \theta_3} & \frac{\partial^2 LL(\theta)}{\partial \theta_3^2} \end{bmatrix} \tag{47}$$

1756 The covariance matrix is then given by:

$$C = [-H]^{-1} = \begin{bmatrix} \sigma_1^2 & \rho_{12}\sigma_1\sigma_2 & \rho_{13}\sigma_1\sigma_3 \\ \rho_{12}\sigma_1\sigma_2 & \sigma_2^2 & \rho_{23}\sigma_2\sigma_3 \\ \rho_{13}\sigma_1\sigma_3 & \rho_{23}\sigma_2\sigma_3 & \sigma_3^2 \end{bmatrix} \tag{48}$$

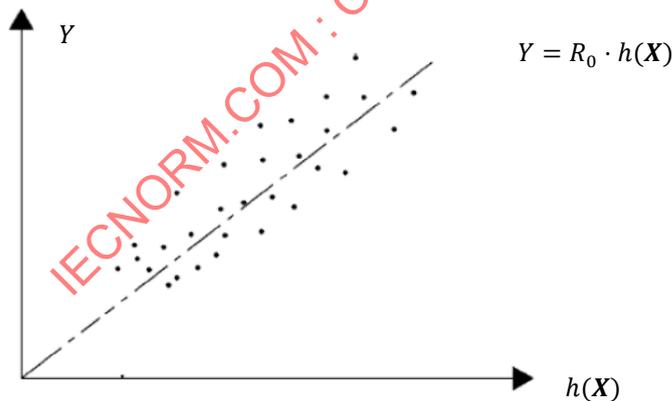
1757 where  $\sigma_j$  is the standard deviation of parameter  $\theta_j$  and  $\rho_{jk}$  is the correlation coefficient between  
1758 parameter  $\theta_j$  and  $\theta_k$ .

1759 The distributions for the parameters become asymptotically (more than 25-30 datapoints) normal  
1760 distributed according to (Lindley 1976).

1761 **A.3 Model Uncertainties**

1762 Model uncertainties should be included in probabilistic models to account for the uncertainty introduced  
1763 by the use of computational models for e.g. resistances and load effects. That is, the differences  
1764 between the measured outcome of an experiment and the prediction based on the mathematical model.  
1765 Ideally, to isolate the model uncertainty, all input parameters to the computational model should be  
1766 measured in relation to the experiment.

1767 To estimate the model uncertainty, the experiment values  $Y$  are plotted as function of model values  
1768  $h(X)$ , as shown in Figure A.2.



1769

1770 **Figure A.2 – Plot for estimation of model uncertainty.**

1771 Often, a lognormal multiplicative model uncertainty is assumed:

$$Y \cong R_0 \cdot h(X) \tag{49}$$

1772 where

- 1773  $Y$  is the test results  
 1774  $R_0$  is a lognormal variable for the model uncertainty with mean  $\mu_0$  and standard deviation  $\sigma_0$   
 1775  $h()$  is the computational model  
 1776  $\mathbf{X}$  is the vector of input parameters (stochastic variables modelling physical uncertainties  
 1777 measured in relation to the experiment)  
 1778

1779 Several approaches can be applied to quantify the model uncertainty, when a sample with values of  $Y$   
 1780 and associated input  $\mathbf{X}$  are available. The Bayesian approach presented in A.1.1 provides an exact  
 1781 solution, when the relation in (6.16) is assumed and the model uncertainty is lognormal. Realizations of  
 1782 the model uncertainty can be evaluated as  $R_{0,i} = Y_i/h(\mathbf{X}_i)$ , and the logarithmic transformation can be  
 1783 applied.

1784 The model with lognormal multiplicative model uncertainty implies that the standard deviation of the  
 1785 error is proportional to the outcome of the computational model, thus for higher values, the error is  
 1786 generally larger, as the coefficient of variation is constant. If the error has constant standard deviation,  
 1787 regardless of the outcome of the computational model, an additive model uncertainty is more  
 1788 appropriate. Here, a normal distribution is often used, as this has a closed form analytical solution.

1789 For distribution types other than normal and lognormal, closed form solutions cannot always be found,  
 1790 but other uncertainty quantification methods, e.g. sampling-based methods, can be used. Sampling-  
 1791 based methods can also be used when measurement uncertainties are to be considered on the  
 1792 measured input and results of the experiments.

1793 IEC 61400-1 ed.4 Annex K uses an alternative method, which has some issues: The use of the “Least  
 1794 Squares” best-fit to estimate the slope  $b$  is inconsistent with the assumption of a lognormal distribution  
 1795 for the error term  $\delta$ , as implicitly assumed. Also, with the applied method, the error term  $\delta$  will generally  
 1796 not have a mean value equal to one, but this is also implicitly assumed.

1797 It should be evaluated whether the assumed model with lognormal distributed multiplicative model  
 1798 uncertainty appropriately describes the data. The following points should be evaluated:

- 1799 • Does  $R_0$  follow a lognormal distribution (does  $\ln(R_0)$  follow a normal distribution)
  - 1800 ○ This can e.g. be evaluated using a qq-plot, a Kolmogorov Smirnov, Shapiro-Wilk, or
  - 1801 Anderson-Darling test.
- 1802 • Is the model uncertainty invariant w.r.t.  $h(\mathbf{X})$ 
  - 1803 ○ This can be evaluated by plotting the sample values of the logarithmic error  $(\ln R_0)_i$  as
  - 1804 function of  $h(\mathbf{x}_i)$ .

1805 A closed form solution can also be found when prior information on the mean and standard deviation is  
 1806 available. Also if the model uncertainty is a normal distributed additive error  $Y \cong R_0 + h(\mathbf{X})$ , an exact  
 1807 closed form solution can be obtained with the methods presented in A.1.1.

### 1808 A.3.1.1 Example: Model uncertainty quantification

1809 This example demonstrates methods for model uncertainty quantification. For the example, theoretical  
 1810 and experimental values of the buckling reduction factor is used for 10 experiments.

#### 1811 Bayesian analytical

1812 The Bayesian approach presented in section A.1.1 provides an exact solution, when the following  
 1813 relation is assumed:

$$Y \cong R_0 h(\mathbf{X}) \quad (50)$$

1814 Table A.1 shows the theoretical and experimental values and the realizations of the model uncertainty  
 1815 calculated as  $R_{0,i} = Y_i/h(\mathbf{X}_i)$ .

1816

**Table A.1 – Theoretical and experimental values**

Experiment number	Theoretical value	Experiment value	Model uncertainty realization
$i$	$h(X_i)$	$Y_i$	$R_{0,i}$
1	1.00	0.750	0.7500
2	2.00	1.599	0.7995
3	3.00	3.053	1.0173
4	4.00	4.153	1.0382
5	5.00	7.468	1.4936
6	6.00	8.066	1.3443
7	7.00	7.093	1.0133
8	8.00	7.828	0.9785
9	9.00	13.285	1.4761
10	10.00	8.760	0.8760

1817

1818 When  $R_0$  follows a lognormal distribution,  $\ln R_0$  follows a normal distribution. The mean and standard  
 1819 deviation of  $\ln R_0$  is found by:

$$m_{\ln R_0} = \frac{1}{n} \sum_{i=1}^n (\ln(R_{0,i})) = 0.0489 \quad (51)$$

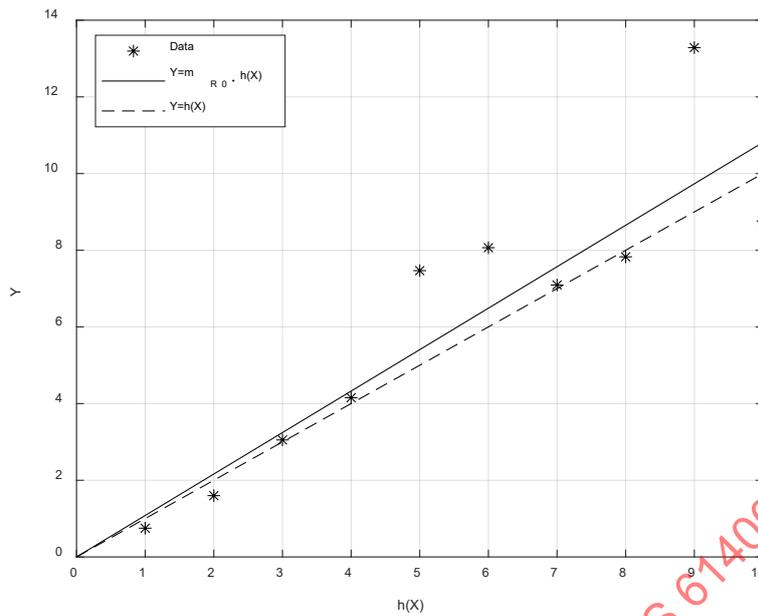
$$s_{\ln R_0} = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (\ln(R_{0,i}) - m_{\ln R_0})^2} = 0.2424 \quad (52)$$

1820 These are the parameters of the estimated lognormal distribution, and the mean and standard deviation  
 1821 are calculated from standard relations:

1822 
$$m_{R_0} = \exp\left(m_{\ln R_0} + \frac{1}{2} s_{\ln R_0}^2\right) = 1.0814$$

1823 
$$s_{R_0} = \sqrt{m_{R_0}^2 (\exp(s_{\ln R_0}^2) - 1)} = 0.2661$$

1824 These are the best estimates for the model uncertainty, but they do not account for statistical uncertainty.



1825

1826

**Figure A.3 – Experiment value Y as function of theoretical value h(x)**

1827 For a sample drawn from  $R_0$ , where both mean and standard deviation are uncertain without  
 1828 any prior information, the predictive distribution for  $\ln R_0$  can be found based on the sample size  
 1829  $n$ , sample mean  $m_{\ln R_0}$  and sample standard deviation  $s_{\ln R_0}$ :

$$\ln R_0 = m_{\ln R_0} + T_{n-1} s_{\ln R_0} \sqrt{1 + \frac{1}{n}}$$

1830

1831 where  $T_{n-1}$  follows a Student's t distribution with  $n-1$  degrees of freedom.

1832 For the model uncertainty  $R_0$ , the predictive distribution accounting for statistical uncertainty is given by:

$$R_0 = \exp(m_{\ln R_0}) \exp\left(T_{n-1} s_{\ln R_0} \sqrt{1 + \frac{1}{n}}\right) \quad (53)$$

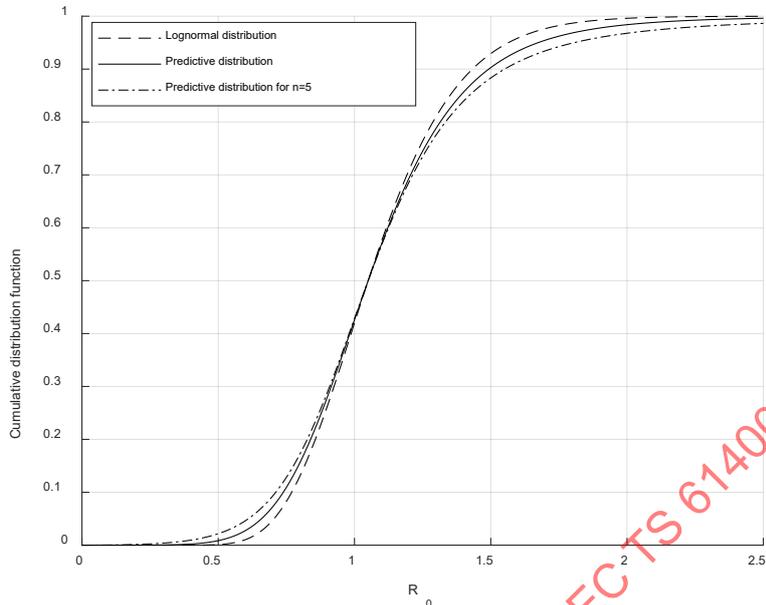
1833 Realizations corresponding to non-exceedance probability  $p$  is found from:

$$r_0(p) = \exp(m_{\ln R_0}) \exp\left(t_{p,n-1} s_{\ln R_0} \sqrt{1 + \frac{1}{n}}\right) \quad (54)$$

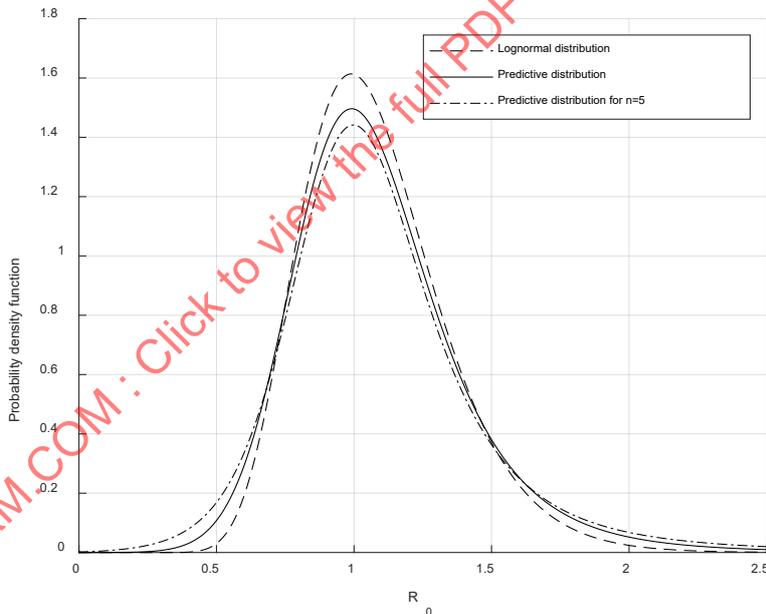
1834 For example, for  $p = 0.05$ , and  $n = 10$ , the Student's t distribution gives  $t_{p,n-1} = -1.8331$ , and  
 1835 thus the equation gives  $r_0(0.05) = 0.6589$ .

1836 Figure A.4 – Cumulative distribution and probability density functions for the predictive  
 1837 distribution, the estimated lognormal distribution and the predictive distribution shows the  
 1838 cumulative distribution and probability density functions for the predictive distribution, The  
 1839 estimated lognormal distribution and the predictive distribution show the obtained cumulative  
 1840 distribution function and probability density function for the predictive distribution, the estimated  
 1841 lognormal distribution (not accounting for statistical uncertainty), and the predictive distribution

1842 if the sample size was instead  $n = 5$ . It is observed that the lower tail is significantly affected by  
1843 the statistical uncertainty for low sample sizes.



1844

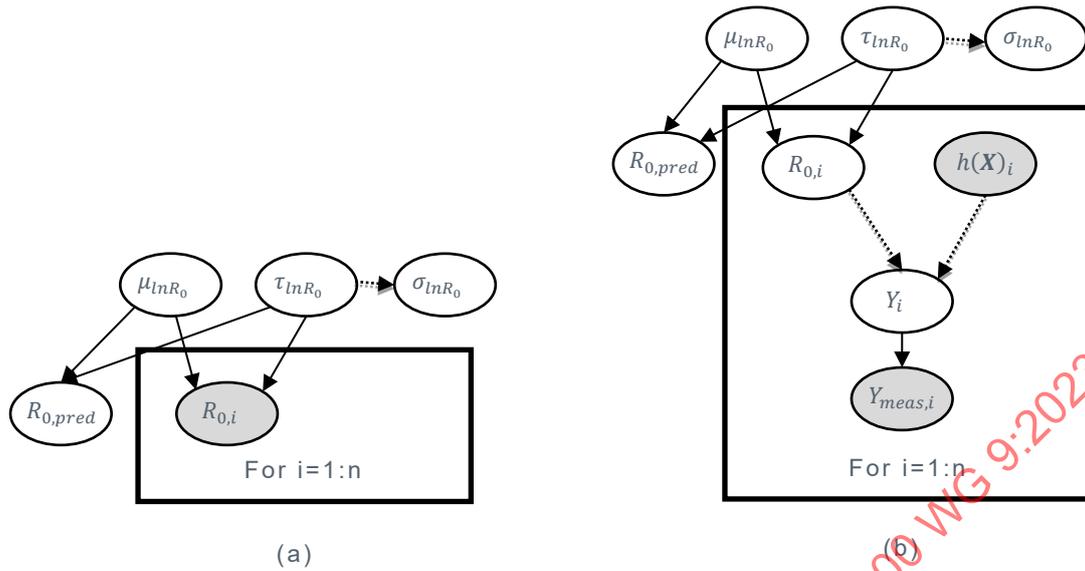


1845

1846 **Figure A.4 – Cumulative distribution and probability density functions for the predictive**  
1847 **distribution, the estimated lognormal distribution and the predictive distribution**

1848 **MCMC methods**

1849 MCMC methods allow working with various distribution types, and there are several ways to  
1850 construct the model for uncertainty quantification. Two models are shown in Figure A.5 a and  
1851 Figure A.5 b for a model without and with measurement uncertainty, respectively. For the model  
1852 without measurement uncertainty, realizations of the model uncertainty are calculated from the  
1853 experiment values and model values:  $R_0 = Y/h(X)$  If the experiment is subject to measurement  
1854 uncertainty, the model value  $h(X)_i$  and the measured values of the experiment outcome  $Y_{meas,i}$   
1855 are used directly.



1856

1857 **Figure A.5 – Various approaches for MCMC models for model uncertainty quantification.**  
 1858 **Full lines represent stochastic relationships, dotted lines represent logic relationship,**  
 1859 **and shaded nodes are observed nodes. (a) without measurement uncertainty, (b) with**  
 1860 **measurement uncertainty.**

1861 Full lines represent stochastic relationships, dotted lines represent logic relationship, and  
 1862 shaded nodes are observed nodes. The nodes  $R_{0,i}$ ,  $h(X)_i$ ,  $Y_i$  and  $Y_{meas,i}$  each have  $n$   
 1863 instantiations; one for each set of values in the sample. The nodes  $\mu_{R_0}$  and  $\tau_{R_0}$  are the nodes  
 1864 for the parameters in the distribution for the model uncertainty, in this case the mean and  
 1865 precision of  $\ln R_0$ . In relation to MCMC, the normal and lognormal distributions are often  
 1866 formulated with the precision ( $\tau_{R_0} = 1/\sigma_{R_0}^2$ ) as second parameter instead of the standard  
 1867 deviation  $\sigma_{R_0}$ . The node  $R_{0,pred}$  is the node for the predictive distribution of the model uncertainty,  
 1868 and it will follow the same distribution as  $R_{0,i}$ , but unlike  $R_{0,i}$ , it is not observed.

1869 If no prior information is available on the parameters  $\mu_{\ln R_0}$  and  $\tau_{\ln R_0}$ , they should be given non-  
 1870 informative priors. For the mean value, an appropriate non-informative prior is a normal  
 1871 distribution, and for the precision, a gamma distribution. Both should have parameters resulting  
 1872 in mean values in the right order of magnitude and sufficiently large standard deviation.

1873 The distributions for model 1 are formulated as follows in the example.

1874 **Table A.2 – Stochastic model**

Variable	Distribution	Parameter 1	Parameter 2
$\mu_{\ln R_0}$	Normal	Mean: $\mu = 0$	Precision: $\tau = 10^{-6}$
$\tau_{\ln R_0}$	Gamma	Shape: $\alpha = 0.001$	Rate: $\beta = 0.001$
$R_{0,i}$	Lognormal	Mean of $\ln R_0$ : $\mu_{\ln R_0}$	Precision of $\ln R_0$ : $\tau_{\ln R_0}$
$R_{0,pred}$	Lognormal	Mean of $\ln R_0$ : $\mu_{\ln R_0}$	Precision of $\ln R_0$ : $\tau_{\ln R_0}$

1875

1876

1877

1878 **Maximum likelihood**

1879 The maximum likelihood method can also be used to estimate the parameters for the model uncertainty  
1880 variable.

1881 As  $R_0$  is assumed to follow a lognormal distribution with parameters  $\mu_{\ln R_0}, \sigma_{\ln R_0}$ , it follows that  $\ln R_0$   
1882 follows a normal distribution with parameters  $\mu_{\ln R_0}, \sigma_{\ln R_0}$ , and can be written based on the standard  
1883 normal density function  $\phi$ :

$$\ln R_0 \sim f_{\ln R_0}(\ln R_0 | \mu_{\ln R_0}, \sigma_{\ln R_0}) = \frac{1}{\sigma_{\ln R_0}} \cdot \phi\left(\frac{\ln R_0 - \mu_{\ln R_0}}{\sigma_{\ln R_0}}\right) \quad (55)$$

1884 The likelihood and loglikelihood function are written as:

$$L(\mu_{\ln R_0}, \sigma_{\ln R_0}) = \prod_{i=1}^n \frac{1}{\sigma_{\ln R_0}} \cdot \phi\left(\frac{\ln R_{0,i} - \mu_{\ln R_0}}{\sigma_{\ln R_0}}\right) \quad (56)$$

$$LL(\mu_{\ln R_0}, \sigma_{\ln R_0}) = \sum_{i=1}^n \ln\left(\frac{1}{\sigma_{\ln R_0}} \cdot \phi\left(\frac{\ln R_{0,i} - \mu_{\ln R_0}}{\sigma_{\ln R_0}}\right)\right) \quad (57)$$

1885 The maximum likelihood estimates of the parameters are found by maximizing  $LL(\mu_{\ln R_0}, \sigma_{\ln R_0})$  with  
1886 respect to the parameters  $\mu_{\ln R_0}, \sigma_{\ln R_0}$  using an optimization algorithm that also provides the hessian  
1887 matrix from which the covariance matrix can be estimated. The parameters are estimated to  
1888  $(\mu_{\ln R_0}, \sigma_{\ln R_0}) = (0.0489, 0.2300)$  and the covariance matrix is estimated to:

$$C = \begin{bmatrix} 0.0053 & 0.0000 \\ 0.0000 & 0.0026 \end{bmatrix}$$

1890 Assuming a multivariate normal distribution for the parameters, samples from the predictive distribution  
1891 can be drawn by first drawing from the multivariate distribution for  $\mu_{\ln R_0}, \sigma_{\ln R_0}$ , and then from  
1892  $R_0 \sim \text{logn}(\mu_{\ln R_0}, \sigma_{\ln R_0})$ .

1893 **Comparison**

1894 Results from the three methods are shown in Table A.3 and Table A.4 and in Figure A.6, Figure A.7,  
1895 Figure A.8 and Figure A.9. The estimated parameters are similar for the three methods, the parameter  
1896  $\sigma_Y$  is smaller for the maximum likelihood method. The reason is that the maximum likelihood method  
1897 finds the mode values of the parameters, and as the standard deviation does not have a symmetric  
1898 distribution, the mode value does not equal the expected value. The quantiles for the maximum  
1899 likelihood method deviates even more, as the distributions for the mean and standard deviation are  
1900 assumed normal distributed, which are not the correct sampling distributions. (The inverse of the  
1901 squared standard deviation follows a gamma distribution, and for a sample size approaching infinity,  
1902 this gamma distribution approaches a normal distribution.)

1903 **Table A.3 – Parameters and moments estimated using each method**

	Parameters		Moments	
	$\mu_{\ln R_0}$	$\sigma_0$	$\mu$	$\sigma$
Analytical	0.0489	0.2424	1.0814	0.2661
MCMC	0.0489	0.2428	1.0815	0.2665
ML	0.0489	0.2300	1.0782	0.2513

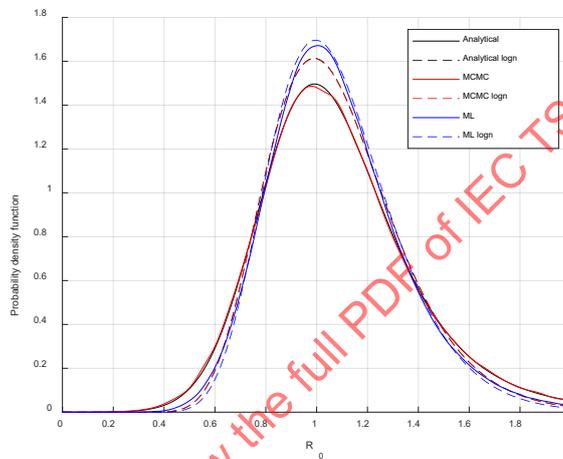
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1905  
1906  
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**Table A.4 – Selected quantiles for the predictive distribution (including statistical/parameter uncertainty) and the fitted lognormal distribution (not including statistical/parameter uncertainty) using each method**

Quantile	Predictive			Lognormal		
	Analytical	MCMC	ML	Analytical	MCMC	ML
0.001	0.3522	0.3428	0.4547	0.4964	0.4958	0.5159
0.01	0.5125	0.5090	0.5772	0.5974	0.5969	0.6150
0.05	0.6589	0.6567	0.7011	0.7048	0.7043	0.7193
0.1	0.7388	0.7376	0.7717	0.7697	0.7693	0.7820

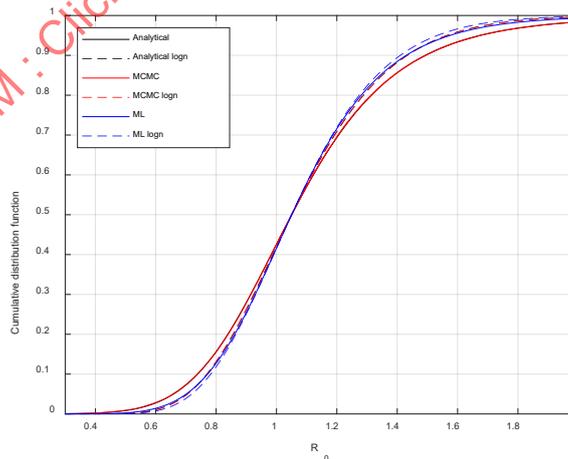
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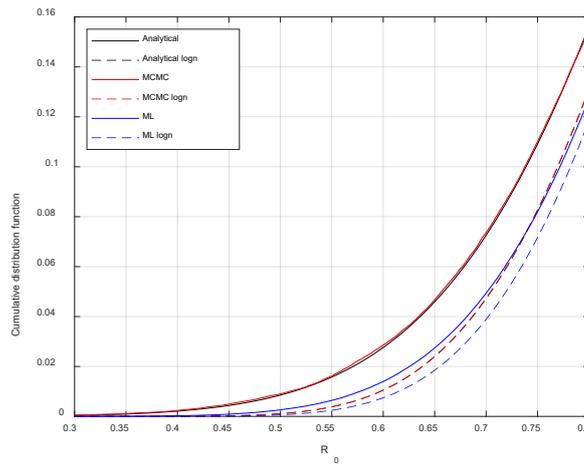
**Figure A.6 – Probability density function for each method**



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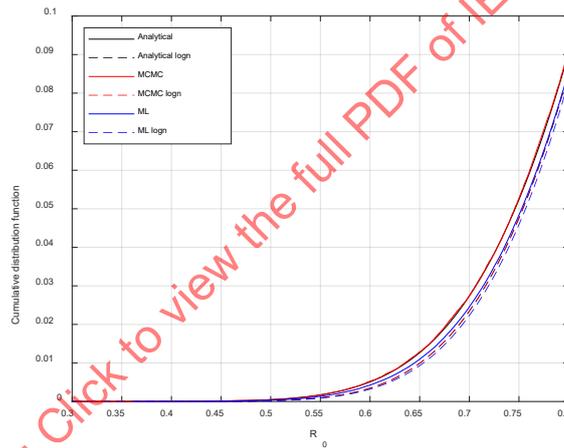
**Figure A.7 – Cumulative distribution function for each method**



1914

1915 **Figure A.8 – Lower tail of the cumulative distribution function for each method**

1916 If the sample size is increased to  $n=50$ , the difference between the methods is much less, and the  
1917 significance of the statistical uncertainty disappears, as seen in Figure A.9. For a lower COV, the  
1918 uncertainty will generally be reduced, and the difference between the methods will be lower.



1919

1920 **Figure A.9 – Lower tail of the cumulative distribution function for each method for a**  
1921 **sample size  $n=50$**   
1922

1923  
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1925  
1926

## Annex B (informative)

### Inverse FORM

1927 Inverse FORM (IFORM), Winterstein et al. (1993), can be applied to find contours for  
1928 environmental conditions with a given probability of exceedance in the long-term joint  
1929 distribution of e.g. mean wind speed and turbulence standard deviation or mean wind speed,  
1930 significant wave height and peak spectral period. IFORM has been applied to derive  
1931 formulations for the turbulence standard deviation conditional on the 10-minute mean wind  
1932 speed for NTM and ETM in IEC 61400-1.

1933 In IFORM, the stochastic variables  $x$  are transformed to the independent standard normal space  
1934 ( $u$ -space) using e.g. the Rosenblatt transformation (Rosenblatt, 1952). A given exceedance  
1935 probability,  $P$ , is associated with any point in  $u$ -space with a distance  $\beta$  to the origin through the  
1936 relation:

$$\beta = -\Phi^{-1}(P) \quad (58)$$

1937 For specific events (such as the number of grid outages, start-ups or shutdowns per year) which  
1938 can be assumed to follow a Poisson process and is independent of the environmental conditions  
1939 the conditional event probability can be introduced directly in the IFORM analysis. Assuming  
1940 that the annual event frequency  $\lambda_E$  is known, the associated conditional distance to the origin  
1941  $\beta_E$  is obtained through the relation:

$$\beta_E = -\Phi^{-1}\left(\frac{P}{\lambda_E}\right) \quad (59)$$

1942 In  $n$  dimensions, the coordinates of the  $u$ -vector  $\mathbf{u}$  should therefore fulfil:

$$\beta = \|\mathbf{u}\| = \sqrt{u_1^2 + \dots + u_n^2} \quad (60)$$

1943 In two dimensions, the points are located on circle with radius  $\beta$ , and pairs of  $u$ -values can be  
1944 found from the following (for all  $\theta$  from 0 to  $2\pi$ ):

$$\begin{aligned} u_1 &= \beta \cos \theta \\ u_2 &= \beta \sin \theta \end{aligned} \quad (61)$$

1945 Corresponding values for each of the variables  $x$ , are found by equating their respective  
1946 distribution functions with the standard normal distribution function, and solving for the variable,  
1947  $x$ :

$$\begin{aligned} F(x) &= \Phi(u) \\ x &= F^{-1}(\Phi(u)) \end{aligned} \quad (62)$$

1948 For example, for the Rayleigh distribution, the distribution function can be written:

$$F(x) = 1 - \exp\left(-\left(\frac{x}{\alpha}\right)^2\right) \quad (63)$$

1949 Solving for  $x$  then yields:

$$x = \alpha \sqrt{-\ln(1 - \Phi(u))} \tag{64}$$

1950 **Example: NTM and ETM model**

1951 This example shows how to use IFORM to calculate environmental contours for the NTM and  
 1952 ETM model. The 10 minute mean wind speed,  $V$ , is assumed to follow a Rayleigh distribution,  
 1953 and the turbulence standard deviation  $\sigma$  follows a Weibull distribution.

1954 a) Select exceedance probability:

1955 The turbulence in NTM corresponds to the 90% quantile in the annual distribution, i.e.  
 1956 it is exceeded 10% of the time:

$$P_{NTM} = 0.1 \tag{65}$$

1957 The turbulence in ETM has an occurrence probability corresponding to 10 minutes out  
 1958 of 50 years.

$$P_{ETM} = \frac{10}{60 \cdot 24 \cdot 365 \cdot 50} = 3.805 \cdot 10^{-7} \tag{66}$$

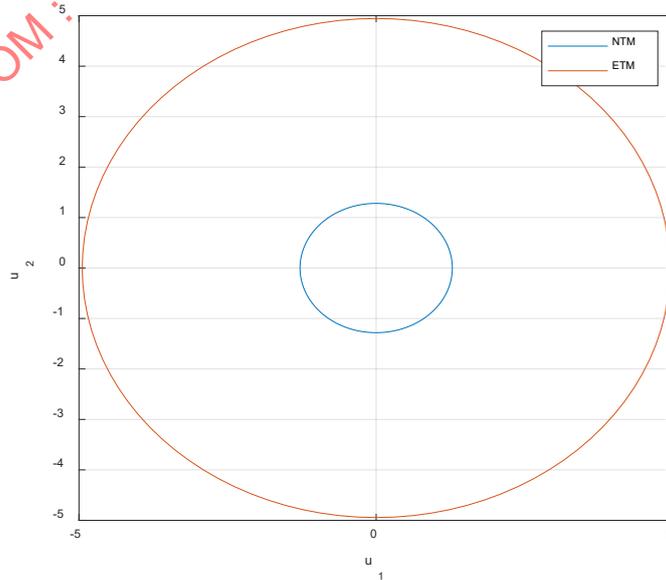
1959 b) Calculate corresponding distance to the origin,  $\beta$ , in standard normal space:

$$\beta_{NTM} = -\Phi^{-1}(P_{NTM}) = 1.282 \tag{67}$$

$$\beta_{ETM} = -\Phi^{-1}(P_{ETM}) = 4.9$$

1960 c) Generate points in u-space with distance  $\beta$  to origin, covering the area of interest:

1961 Using equations (60) and (61) with values of  $\theta$  in the range from 0 to  $2\pi$ , Figure B.1 is  
 1962 generated:



1963

1964

**Figure B.1 – Contour lines for NTM and ETM in the u-space**

1965 d) Calculate x-vectors corresponding to the points in u-space using the inverse cumulative  
1966 distribution functions.

1967 Here  $x_1 = V$  and  $x_2 = \sigma$ .

1968 For the 10 minute mean wind speed, a Rayleigh distributed variable with mean  $\mu_V$ , the  
1969 transformation is:

$$V(u_1) = \frac{2\mu_V}{\sqrt{\pi}} \sqrt{-\ln(1 - \Phi(u_1))} \quad (68)$$

1970 The turbulence standard deviation  $\sigma$  is assumed to follow a Weibull distribution with shape  
1971 parameter  $k$  and scale parameter  $C$ , both conditioned on the wind speed:

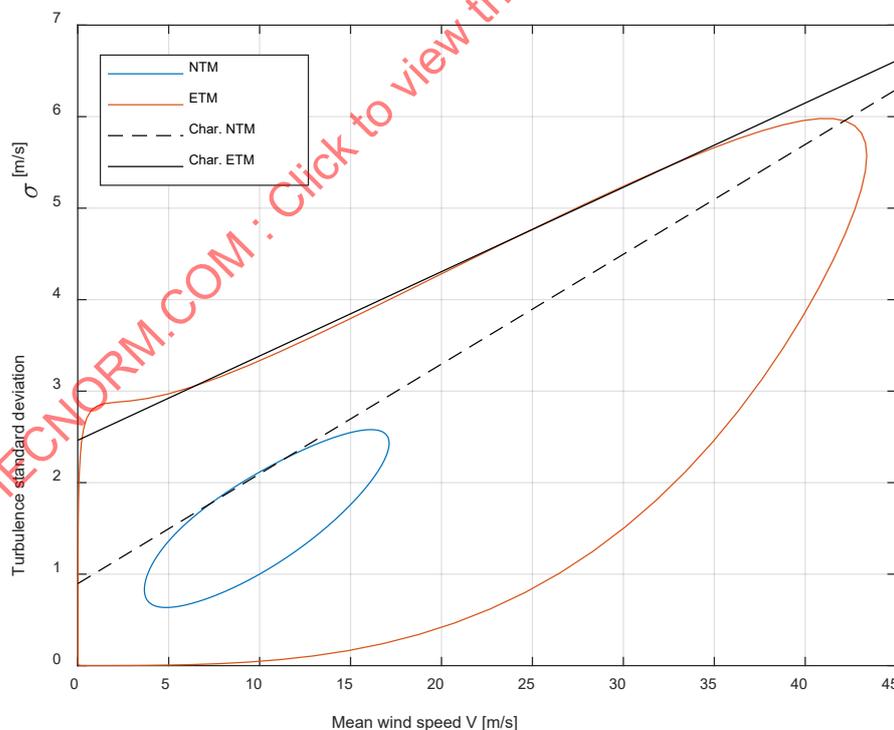
$$k(u_1) = 0.27 V(u_1) + 1.4 \quad (69)$$

$$C(u_1) = I_{ref}(0.75 V(u_1) + 3.3)$$

1972 Values of the turbulence standard deviation are then calculated from:

$$\sigma(u_1, u_2) = C(u_1) \cdot (-\ln(1 - \Phi(u_2)))^{\frac{1}{k(u_1)}} \quad (70)$$

1973 For IEC class IA, the mean  $\mu_V$  is 10 m/s, and the turbulence intensity  $I_{ref}$  is 0.16. Figure B.2  
1974 shows the contours for NTM and ETM together with the characteristic values defined in IEC  
1975 61400-1 ed. 4.



1976

1977 **Figure B.2 – Contour lines for NTM and ETM, and the characteristic values defined in**  
1978 **IEC61400-1**

1979

1980

**Annex C  
(informative)**

**Example Calculations for Reliability Assessment**

1981  
1982  
1983  
1984

1985 The purpose of this information annex is to provide some representative probabilistic models for the  
1986 main wind turbine components (Tower) and design situations (DLC 1.2, 1.3 & 6.1) in order to describe  
1987 the background for the partial safety factors in the IEC 61400-1 standard.

1988 The representative probabilistic models can either be tailored directly to a specific wind turbine  
1989 design or used as a baseline to define probabilistic models for other main wind turbine  
1990 components or design situations.

1991 **C.1 Ultimate Limit State**

1992 **C.1.1 Design Equation**

1993 The design equation is defined according to IEC 61400-1 4<sup>th</sup> edition equation (29) and (30):

$$G = z \frac{1}{\gamma_M} R_k - \gamma_f L_k \geq 0 \tag{71}$$

1994 where  $z$  is a design parameter (which may be used to scaled the design equation to the limit  
1995  $G=0$ ),  $\gamma_M$  is the partial safety factor for material parameters and resistance models,  $R_k$  is the  
1996 characteristic value for the resistance,  $\gamma_f$  is the partial safety factor for loads and  $L_k$  is the  
1997 characteristic value for the loads. The partial safety factor for consequences of failure  $\gamma_n$  is  
1998 implicitly assumed to 1.0 corresponding to component class 2.

1999 **C.1.2 Limit State Equation**

2000 The limit state function is defined as:

$$g = z \delta R X_{Str} - X_{Site} X_{Aero} X_{Dyn} X_{Mat} X_{Wind} X_{Sim} L \tag{72}$$

2001 where  $\delta$  is the model uncertainty for the resistance model,  $R$  is the physical, model and  
2002 statistical uncertainty in the dominating strength parameter and  $X_{Str}$  is the model uncertainty in  
2003 the stress / strain model.

2004  $X_{Site}$  is the physical, model, statistical and measurement uncertainty in the site / atmospheric  
2005 conditions, see Annex G,  $X_{Aero}$  is the physical and model uncertainty in the aerodynamic  
2006 properties,  $X_{Dyn}$  is the model uncertainty in the aeroelastic model,  $X_{Mat}$  is the physical  
2007 uncertainty in the material and geometrical properties,  $X_{Wind}$  is the model uncertainty in the  
2008 wind model e.g. turbulence box and wake modelling,  $X_{Sim}$  is the statistical uncertainty in the  
2009 simulation setup and  $L$  is the physical uncertainty in the load effect.

2010 The uncertainties in the loading conditions are (when relevant) assumed propagated through  
2011 the aeroelastic model to the load parameter of interest, see section 6.3.2. The stochastic  
2012 variable  $F$  is normally determined by fitting a distribution function to the load parameter  
2013 evaluated for different quantiles of dominating environmental conditions e.g. extreme  
2014 turbulence in DLC 1.3 and extreme mean wind speeds in DLC 6.1.

2015 The baseline stochastic variables are listed in Table C.1 – for wind loading (normal operation /  
2016 idling) and gravity loading along with the resistance (Steel).

2017

**Table C.1 – Baseline stochastic variables for load and resistance model.**

Variable	Distribution	Mean	Char.	COV	Wind Loading Normal Operation	Wind Loading Idling	Gravity Loading
$X_{\text{Site}}$	LN	1.00	$\mu$	10%	10%	10%	0%
$X_{\text{Aero}}$	LN	1.00	$\mu$	10%	10%	10%	0%
$X_{\text{Dyn}}$	LN	1.00	$\mu$	5%	5%	5%	0%
$X_{\text{Mat}}$	LN	1.00	$\mu$	5%	5%	5%	5%
$X_{\text{Wind}}$	LN	1.00	$\mu$	10%	10%	10%	0%
$X_{\text{Sim}}$	LN	1.00	$\mu$	5%	5%	5%	0%
L	G / G / N	-	98% / 98% / $\mu$	5%	23%	23%	5%
$\delta$	LN	1.00	$\mu$	5%			
R (Steel)	LN	-	5%	5%			
$X_{\text{Str}}$	LN	1.00	$\mu$	5%			

2018

### 2019 C.1.3 Reliability Assessment

2020 The annual reliability index for the different wind turbine components and design situation are  
 2021 estimated using the First Order Reliability Method (FORM) and listed in Table C.2 – . The  
 2022 estimate reliability index is for DLC 1.3, DLC 6.1 and Gravity loading close to the target reliability  
 2023 index of 3.3 according to 5.

2024 **Table C.2 – Annual reliability index for different main wind turbine components (Tower)**  
 2025 **and design situations (DLC 1.3 & 6.1).**

Material	$\gamma_M$	Wind Loading Normal Operation DLC 1.3	Wind Loading Idling DLC 6.1	Gravity Loading
$\gamma_f$		1.35	1.35	1.10
Steel	1.20	$\beta = 3.26$	$\beta = 3.29$	$\beta = 3.22$

2026

### 2027 C.1.4 Direct reliability-based design

2028 In the case of direct reliability design, one can solve for the probability of failure for various  
 2029 values  $z$  of the design parameter. This method obviates the use of the design equation and its  
 2030 associated safety factors, as the required safety is obtained directly through the calculation of  
 2031 the design parameter  $z$  required to achieve the target reliability level.

2032 An example is provided for the probabilistic model in Table C.1 – above and focusing on the  
 2033 case of an analysis of a steel component under normal operation conditions. For the direct  
 2034 reliability calculation, distributions for load and resistance need to be fully characterized, and  
 2035 in this example we choose (arbitrarily) reference values of 1.0 for both the characteristic levels  
 2036 of load ( $F_K$ , or the 98% quantile of the load distribution) and resistance ( $R_K$ , or the 5% quantile  
 2037 of the material strength distribution), we use FORM to obtain the results shown in Table C.3 –  
 2038 for reliability index as a function of design parameter  $z$ .

2039  
2040

**Table C.3 – Resulting reliability index for different values of design parameter for simplified example**

$z$	1.45	1.55	1.65	1.75
$\beta$	2.76	3.06	3.34	3.61

2041  
2042

Alternatively, one can also iteratively calculate the value of design parameter that will meet a desired, pre-assigned, reliability level.

2043

**C.1.5 Reliability-based calibration of partial safety factors**

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In a different application case – going back to the use of the design equation and partial safety factors – suppose new information collected substantiates the argumentation that, for a given site where a more accurate combination of models and measurements is used, the coefficient of variation of  $X_{Site}$  is reduced to 0.05. In such cases, one could calibrate a new safety factor for loads following the same procedure outlined above.

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Again, starting from the baseline probabilistic model assumed for steel components and normal operating conditions stated in Table C.1 – above, Table C.4 – shows the results for the reliability index for several different values of the safety factor choice  $\gamma_f$  given  $\gamma_M = 1.20$  (the only applicable choices would be the ones resulting in a reliability index higher than 3.3):

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**Table C.4 – Resulting reliability for different partial safety factor for loads (given  $\gamma_M = 1.2$ )**

$\gamma_f$	1.20	1.25	1.30	1.35
$\beta$	2.95	3.15	3.34	3.53

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**C.1.6 Assess the accuracy of the computation and perform sensitivity studies**

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Assume a designer has chosen the design parameter  $z = 1.65$  from the calculation outlined in

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C.1.1 to meet a target reliability of  $\beta = 3.34$ . One may estimate and justify the accuracy of this solution by applying a direct simulation method such as a crude Monte Carlo.

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In a crude Monte Carlo, all the random variables composing the limit state equation are randomly drawn from their respective distributions defined in Table C.1 a sufficiently large number of times and the probability of failure is estimated as the relative number of times the resulting limit state equation is lower than 0. Table C.5 shows the estimated probability of failure as the number of Monte Carlo runs increases in magnitude.

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**Table C.5 – Assessment of reliability index convergence with number of draws in Monte Carlo simulations**

$N$	$10^4$	$10^5$	$10^6$	$10^7$
$\beta$	3.23	3.27	3.27	3.27

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From Table C.5 one concludes that the reliability index is converging to  $\beta = 3.27$  which is within 2.5% of the value obtained by FORM. For more complex cases and limit states, one notes that the accuracy of FORM might not be guaranteed to be of this magnitude. Alternatives are the use of Second Order Reliability Method (SORM) and other direct simulation techniques such as adaptive importance sampling.

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There are several ways that one can assess the sensitivity of the results from a reliability analysis with respect to input variables of interest. Here two of such ways are listed.