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Holistic Asset Management Concept for Wind Turbines using Nondestructive Testing and Structural Health Monitoring Techniques

Christian Timo Geiss (M.Sc.)

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Vorsitzender: Prof. Dr. phil. Carlo Bottasso

Prüfer: 1. Prof. Dr.-Ing. Christian Große

2. Prof. Dr.-Ing. Eugen Brühwiler

École Polytechnique Fédérale de Lausanne

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Für Dich, Chef.

1959 – 2012

„Never give in, never give in, never, never, never, never—in nothing, great or small, large or petty—never give in except to convictions of honor and good sense.”

Winston Churchill, October 29, 1941, Harrow School Speech (Churchill 1941).

I. VORWORT UND DANKSAGUNG

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München, im Juli 2018

II. ABSTRACT

In the future market environment of renewable energy sources – especially for onshore wind energy systems – economic and cost-effective operation will play a key role. This prognosis is valid both for macro and micro economical frameworks, e.g. for the global environment as well as for the single wind turbine operator. One of the biggest challenges in energy and macro economical politics will be to steer through the tension field of energy transition from fossil and nuclear sources to renewable energy sources, while at the same time sustaining international competitiveness in the cost of production and ensuring a reasonable reliability level of the systems. The application of condition monitoring and nondestructive testing techniques within an integrated and holistic asset management approach can significantly contribute to this.

The thesis shows how nondestructive testing and structural health monitoring techniques can be applied to establish new efficient and sustainable maintenance strategies for wind turbine systems in a holistic asset management framework. Existing maintenance strategies are investigated in a wider frame. Furthermore, a qualitative risk analysis determines the more critical parts of a wind turbine system. State of the art NDT and SHM techniques are evaluated concerning their potential to contribute to quality control, conservation and sustainability of wind turbine systems. A combination of different NDT and SHM techniques was found to be the most successful approach to new inspection strategies.

III. KURZZUSAMMENFASSUNG

Im zukünftigen Marktumfeld der erneuerbaren Energie, wird zunehmend der kostenoptimale Betrieb von Windenergieanlagen eine entscheidende Rolle spielen. Das gilt sowohl für die volkswirtschaftlichen Rahmenbedingungen in Zukunft, als auch für die betriebswirtschaftlichen Ziele der einzelnen Turbinenbetreiber. Eine der größten Herausforderungen der Energiewende wird es dabei sein, die bisher geförderte Einspeisung von Windenergie durch das Spannungsfeld eines zunehmend kompetitiven Strommarktes zu steuern. Daher rücken ganzheitliche Instandhaltungssysteme für Windenergieanlagen stärker in den Fokus. Zielsetzung ganzheitlicher Instandhaltungssysteme muss es sein, einen kostenoptimalen Anlagenzustand und Systemverfügbarkeit bereitzustellen. Der Einsatz von zerstörungsfreien Prüf- und Dauerüberwachungsverfahren, eignet sich unter dieser Prämisse besonders, einen signifikanten Beitrag zu dieser übergeordneten Zielsetzung zu liefern. Gegenstand dieser Arbeit ist es einen ganzheitlichen Anlagenmanagementansatz zu entwickeln, diesen zu implementieren und auf seine Wirksamkeit hin zu analysieren.

Keywords: Asset management, wind turbine, structural health monitoring, condition monitoring, nondestructive testing, risk-based inspections, ontologies, remaining useful life.

IV. TABLE OF CONTENTS

V. LIST OF FIGURES

VI. LIST OF TABLES

VII. LIST OF ABBREVIATIONS

AD	Anno domini
ADT	Annual down time
AM	Asset management
AMP	Asset management plan
ANN	Artificial neural networks
BC	Before Christ
BSH	Bundesamt für Seeschifffahrt und Hydrographie / Federal Maritime and Hydrographic Agency in Germany
BSI	British Standard Institution
BWE	Bundesverband WindEnergie e.V./ German Wind Energy Association
CAE	Computer aided engineering
CAPEX	Capital expenditures
CB-RA	Cost-based risk analysis
CFRP	Carbon-fiber reinforced plastics
CMS	Condition monitoring system
CMMS	Computerized maintenance management systems
CREW	Continuous Reliability Enhancement for Wind
CUF	Cumulative usage factor
CUF	Cumulative usage factor
CVPI	Conditional value of perfect information
CVSI	Conditional value of sample information
DEL	Damage equivalent loads
DEWI	DEWI GmbH - Deutsches Windenergieinstitut / German Wind Energy Institute GmbH
DGZfP	Deutsche Gesellschaft für Zerstörungsfreie Prüfung / German Society for Nondestructive Testing
DIBt	Deutsches Institut für Bautechnik / German Centre of Competence for Construction
DIN	Deutsches Institut für Normung e.V. / German Standardization Institute
DNV	Det Norske Veritas
DS	Danish Standard
EMS	Engine management systems
EPFL-MCS	École Polytechnique Fédérale de Lausanne – Laboratory of Maintenance and Safety of Structures
ERM	Entity relationship model
EU	European Union
EVPI	Expected value of perfect information
EVSI	Expected value of sample information
FA	Fore-aft direction
FAMOS	Fatigue Monitoring System
FBG	Fiber Bragg Grating
FCA	Fatigue critical area
FE	Finite elements
FEM	Finite element method
FATIWIND	Fast fatigue analysis for wind turbines
FFC	Fast fatigue check
FFT	Fast Fourier Transformation

FhG IWES	Fraunhofer Institut für Windenergie und Energiesystemtechnik / Fraunhofer Institute for Wind Energy and Energy System Technology
FM	Fracture mechanics
FMEA	Failure Mode and Effect Analysis
FMEA	Failure-Mode-and-Effect-Analysis
FMECA	Failure-Mode-Effect-and-Criticality-Analysis
FMEDA	Failure-Mode-Effect-and-Detectability-Analysis
FORM	First-Order-Reliability-Method
FPI	Fatigue performance indicator
FTA	Fault-tree analysis
GFRP	Glass-fiber reinforced plastics
GL	Germanischer Lloyd
GLONASS	Globalnaja nawigazionnaja sputnikowaja Sistema (Russian for: Global Navigation Satelite System)
GNSS	Global Navigation Satelite Systems
GPS	Global Positioning System
GROWIAN	Große Windenergieanlage / German Acronym for: Big Wind Turbine System
GtCO2e	Gigatonnes of equivalent carbon dioxide
HSS	High speed shaft
HUMS	Health and Usage Monitoring System
IABG	Industrieanlagen-Betriebsgesellschaft mbH
IAM	Institute of Asset Management
IAMS	Integrated Asset Management System
IAMS-Wind	Integrated Asset Management System for Wind Turbines
IEA	International Energy Agency
IEC	International Electrotechnical Commission
ILS	Integrated Logistic Support
ISO	International Organization for Standardization
KEMA	Keuring van Elektrotechnische Materialen te Arnhem / Certification authority in the Netherlands
KISSY	Kraftwerksinformations-system
KPI	Key performance indicator
KPIS	Key performance indicator system
LCC	Life cycle costing
LCF	Life cycle file
LCOE	Levelized cost of energy
LCP	Life cycle phase
LIDAR	Lightning Detection and Ranging
MAN	Maschinenfabrik-Augsburg-Nürnberg
MBB	Messerschmitt-Bölkow-Blohm
MEMS	Micro-electromechanical systems
MI	Monitoring and inspection

MISTRAL-WIND	Monitoring and Inspection of Structures at Large Wind Turbines
MIT-DB	Monitoring and inspection technique database
MMP	Maintenance master plan
MOR	Model order reduction
MPC	Model predictive control
MS Excel	Microsoft Excel spreadsheet
MTBF	Mean time between failure
MTTR	Mean time to repair
NASA	National Aeronautics and Space Administration
NPV	Net present value
NREL	National Renewable Energy Laboratory
O&M	Operation and maintenance
OCM	Oil condition monitoring
ODBMS	Operational database management systems
OEM	Original equipment manufacturers
OMA	Operational modal analysis
OPEX	Operational expenditures
OREDA	Offshore and Onshore Reliability Data
OWL	Web Ontology Language
PDA	Personal Digital Assistant
PDF	Probability density function
PF-diagram	Potential failure diagram
PFI	Probability of false indication
POD	Probability of detection
POI	Probability of indication
RBI	Risk-based inspections
RCM	Reliability-centered maintenance
RFID	Radio-frequency identification
RMS	Root-mean-square
RPN	Risk priority number
RQ	Research question
RTK-GPS	Real-Time-Kinematic GPS
RUL	Remaining useful life
SAMP	Strategic Asset Management Plan
SCADA	Supervisory Control and Data Acquisition
SCADA-FMC	SCADA-Fleet-Management-Concept
SHM	Structural health monitoring
SLS	Servicablity limit state
SNR	Signal-to-noise ratio
SODAR	Sonic Detection and Ranging
SORM	Second-Order-Reliability-Method
SRA	Structural reliability analysis
SRC	Steel-reinforced concrete
SRU	Smallest replaceable unit
SSI-COV	Covariance driven stochastic subspace identification
STFT	Short-time Fourier transform
TCO	Total Cost of Ownership
TRL	Technology readiness level
UHPC	Ultra-high-performance-concrete
UHPFRC	Ultra-high-performance-fiber-reinforced-concrete

UNFCC	United Nations Framework Convention on Climate Change
UK	United Kingdom
USA	United States of America
VGB	Vereinigung der Großkesselbesitzer e.V / German Industrial Vessel Association
W3C	World Wide Web Consortium
WACC	Weighted Average Cost of Capital
WMEP	Wissenschaftliches Mess- und Evaluierungsprogramm / Scientific Measuring and Evaluation Program
WP	Work package
WT	Wind turbine

VIII. LIST OF SYMBOLS

Latin

a - Scale parameter of *Weibull*-distribution

a_0 - Initial crack dimension [mm]

a_{cr} - Critical crack dimension [mm]

a_D - Action in decision theory

$a(n)$ - Crack dimension after N-cycles [mm]

$\vec{a}(t)$ - Acceleration of a body over time [m/s²]

A - scaling parameter [m/s]

A_R - Control surface of rotor [m²]

$ACB{-}RPN_i$ - Annual cost-based risk priority number [€]

c_P - Power coefficient

c_S - Thrust coefficient

c_{PL} - Production loss factor

C - Fracture mechanics material parameter

C_i - Consequences of a specific event

$C_{i,R}$ - Cost of repair or replacement of the specific sub-assembly [€]

$C_{i,L}$ - Logistic cost of equipping maintenance crew [€]

$C_{i,M}$ - Manpower cost of the specific maintenance task [€]

$C_{i,P}$ - Opportunity cost of the production loss resulting from the turbine's failure case [€]

$CB{-}RPN_i$ - Cost-Based-Risk-Priority-Number [€]

C_t - Annual cost [€]

C_x - Material parameter

d_D - Decision rule

d - Offset of boundary layer from ground [m]

d_{TT} - Tower top displacement [m]

D - Detectability of failure mode

D_x - Fatigue damage

D_R - Rotor diameter [m]

e - Inspections; number, time, location and type of inspections

E - E-modulus [N/m²]

EP - Unity cost of energy [€/MWh]

E_{ext} - Extracted kinetic energy [J]

E_{kin} - Kinetic energy [J]

$E(N_{i,FV})$ - Expected number of failure vulnerabilities per year

E_I - Event of indication of a defect

E_D - Event of detection of a defect

E_{FI} - Event of false indication

E_{s_m} - Event of a defect measurement with a measured size s_m

E_X - Probabilistic event

f_c - Static compressive strength of concrete [N/m²]

$f_{\Delta S}(\Delta S)$ - Stress range distribution [N/m²]

$f_{\underline{x}}(\underline{x})$ - Probability density function

F_{eq} - Equivalent load [N]

$\Delta F_{i,t}$ - Load component in wind turbine fleet leader concept [N]

F_S - Wind thrust force [N]

F_T- Axial thrust force drive shaft [N]

FPI_{QI} - Fatigue Performance Indicator Quality Index

$g(x)$ - Limit state function

h_a - Averaging parameter for fleet leader concept

h_x - Wind speed height [m]

I_0 - Initial investment cost [€]

$I_{x,y,z}$ - Turbulence intensity [%]

k - Shape parameter of *Weibull*-distribution

k_f - Total number of potential and known failures

k_{PN} -Parameter determining the nature of the process

k_1 - Gradient parameter

k_2 - Gradient parameter

K - Stress intensity factor

l - Defect length [mm]

l_{TL} - Tower length [m]

m - Mass [kg]

m_W- S-N exponent

m_x - Material parameter

M - Rotor torque [Nm]

M_B - Rotor bending moment [Nm]

M_T - Torsional moment [Nm]

n - Rotor speed [m/s]

n_x - Number of decision tree branches

$n_{Cladding}$ - Refractive index of FBG cladding

n_{Core} - Refractive Index of FBG core

n_{eq} - Reference load cycles

n_{in} - Incoming gear box shaft speed [1/s]

N - Number of load cycles

$N_{i,F}$ - Sum of number of actual failures

$N_{i,D}$ - Sum of number of detected failure before occurrence

ND_i - Not-detection-probability

O_i - Occurrence of the specific failure mode

P - Probability of failure mode

$P(a(n))$ - Probability of crack size after a specific number of cycles

$P_F(t)$ - Failure probability for a specific period of time

POD - Probability of detection

P_i - Probability of a specific event

P_{mech} - Mechanical performance [W]

P_{el} - Electrical power [W]

r - Interest rate [%]

$r(t)$ - Reliability of a system at time t

R - Risk of a specific event

R_S - Mean stress ration [N/m^2]

RPN - Risk Priority Number

s - Defect size [mm]

s_x - Standard deviation

$\vec{s}(t)$ - Displacement of a body over time [m]

S - Severity of failure mode

S_X - Normalized concrete loading [N/m²]

S_{HS} - Hot spot stress [N/m²]

S_N - Notch stress [N/m²]

$t_{d,i}$ - Respective downtime of the relevant failure case [h]

t_{meas} - Measured time [a]

t_{op} - Operative time [a]

t_{RUL} - Remaining useful lifetime [a]

T_{SL} - Service life period [a]

u - Rotor tip speed [m/s]

u_D - Utility index in decision theory

U - Average wind speed in specific time interval [m/s]

U_R - Uniformly random distributed variable

v - Wind speed [m/s]

v_1 - Free wind inflow speed [m/s]

$\bar{v}$ - Average wind speed [m/s]

$\vec{v}(t)$ - Speed of a body over time [m/s]

$v_{Rot,up}$ - Wind speed at upper rotor position [m/s]

$v_{Rot,down}$ - Wind speed at lower rotor position [m/s]

$v_{nacelle}$ - Wind speed at hub height [m/s]

w - Capacity factor

W - Nominal electrical capacity [MW]

$y(t)$ - Damage indicator [-]

Y_{el} - Energy yield [MWh]

$Y_G(a)$ - Geometric fracture mechanics factor

$\bar{x}$ - Mean value

$z(t)$ - process of disturbances

z_0 - Roughness length [m]

Z - Inspection outcomes: no detections, detections, observed crack dimension

<u>Greek</u>

α_{2D} - Parameter of the 2D-POD model

α_{FL} - Scaling parameter for fleet leader concept

β - Reliability index

$\beta_{D,a}$ - Parameter of the 2D-POD model

σ - Stress [N/m²]

σ_B - Bending stress [N/m²]

σ_U - Standard deviation of wind speed in specific time interval [m/s]

Δ - Damage limit

Δs - Crack dimension [mm]

ΔS - Stress range

ΔS_0 - Cut-off fatigue stress range [N/m²]

$\Delta\sigma_{R_{Sk}}$ - Yield strength [N/m²]

ε - Refraction angle of FBG sensor [°]

ε_m - Measurement error [mm]

ε_T - Tower strain [m/m]

Θ - True state in decision theory

$\upsilon_t(\theta)$ - Conditional value of perfect information

ν - Stress cycle rate

$\varphi(u_i)$ - Independent standard normal distribution function

Φ - Standard normal distribution function

λ - Tip speed ratio

λ_B - *Bragg*-Wave-Length [nm]

λ_i - Failure rate

Λ - Refraction index modulation [°]

$\Psi(y)$ - Integral function of y^{-k}

$\chi(t)$ - Integral of $h\big(z(\tau)\big)$

μ - Mean time to failure in probab. model [d]

γ_{max} - Total reflection angle of FBG sensor [°]

$x(\tau)$ - Vector of basic variable at time τ

Ω - Angular frequency [1/s]

1 INTRODUCTION – TAILWIND TO THE FUTURE

Figure 1-1: Alaskan glacier in public domain (Cowan 2016).

„When considering the history of human civilization, the shift to renewable energy sources is of great significance. That is why this process must be accelerated. Renewable energy sources are not limited – but time is." - (Scheer 2011)

1.1 CLIMATE CHANGE IN THE 21ST CENTURY

Human population on this planet can be seen as the leading cause for recent and future climate change, we will experience. 90 % of the human climate implications can be traced back to the combustion of fossil fuels. By the middle of the 21st century, the average global warming will be at least 1.5 °C above the level in pre-industrial ages. This irreversible climate effect will cause crop failures, increasing risk of flooding on coastal areas and diminishing water resources. Especially at risk are developing and emerging countries and economies, because combusting fossil fuels is seen as the key to the long-desired prosperity. To limit the average global warming to a maximum temperature increase of 2 °C, the global population has to limit the cumulative carbon dioxide emissions produced as of 1870 to a maximum amount of 2,900 giga tons. By 2011, the international community had already emitted two thirds of this “credit amount”, thus leaving a mere 1,000 giga tons of admissible emissions for the current global generation. If we do not radically change our energy system, but pursue the current situation, our carbon dioxide budget will run out within the next 30 years (Edenhofer 2012).

Carbon dioxide emissions represent quantitively the highest amount of greenhouse gas emissions out of several other gases damaging the atmosphere, such as methane, ozone and nitrous oxides (Olivier et al. 2017).

The German Federal Government pursues the goal of reducing greenhouse gas emissions by about 40 % until the year 2020, compared to the emission level in 1990. Currently the emissions have only been reduced by about 24 %. Should this level of emissions remain, in 2020, Germany will be emitting 90 mega tons more carbon dioxide than agreed on in this energy transition plan. One ton of carbon dioxide causes a climate damage which can be rated about 80 €. This means that the current emission course will lead to an additional climate damage of about 7.2 billion €. The coalition under chancellor Merkel agreed on a long term emission goal to reduce greenhouse gas emissions to 80 … 95 % until the year 2050 (Aykut 2015; Bundesministerium für Wirtschaft und Energie 2016).

Ten years ago, the widely known “Stern report” was released for the Government of the United Kingdom by Nicholas Stern, chair of the Grantham Research Institute on Climate Change and the Environment at the London School of Economics. The report discussed the impact of global climate change from an economical point of view. Stern states that climate change is the greatest and widest ranging market failure ever seen in history. Statistics and research on climate change may have developed in the past years, but the main conclusion of the report has more relevance than ever before: The benefits of strong, disruptive, and early actions on climate change will by far outweigh the cost of not acting or retaining (Stern 2011).

This thesis lives by the motivation to contribute to the fight against climate change.

1.2 THE ROLE OF WIND ENERGY

The United Nations involve in global strategies to comply with the international climate goal to keep global warming in this century below 1.5 °C on average as stated in the Paris Agreement (United Nations 2015). Therefore, the United Nations Framework Convention on Climate Change (UNFCC) seeks for additional technological potentials to lower greenhouse gas emissions. Figure 1-2 shows possible additional total emission reduction potentials per year and sector. The total emission reduction potential sums up to approximately 33 giga tons of carbon dioxide equivalent per year. Realizing this potential would be sufficient to keep the climate within the stated 1.5 °C goal with a probability of 66% (The Emissions Gap Report 2017).

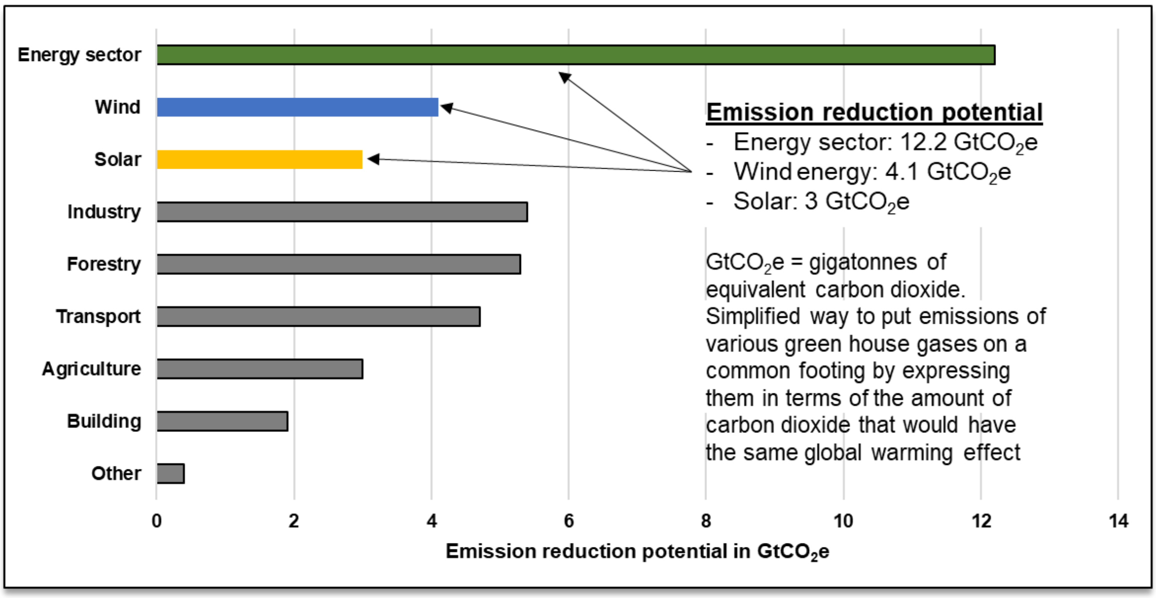


Figure 1-2: Sectoral annual additional emission reduction potential in $GtCO_2e$ until 2030 – adapted from (The Emissions Gap Report 2017)

From this, as well as from the following considerations, the key role an economic operation of wind energy systems plays in the fight against global climate change becomes apparent.

29 % of the German energy consumption is already provided by renewable energy sources. Wind energy is represented by a share of 12 % (Bange et al. 2017).

In the future market environment of renewable energy sources – especially for onshore wind energy systems – economic and cost-effective operation will play a key role. This prognosis is valid both for macro and micro economical frameworks, e.g. for the global environment as well as for the single wind turbine operator. One of the biggest challenges in energy and macro economical politics will be to steer through the tension field of energy transition from fossil and nuclear sources to renewable energy sources, while at the same time sustaining international competitiveness in the cost of production and ensuring a reasonable reliability level of the systems. The application of condition monitoring and nondestructive testing techniques within an integrated and holistic asset management approach can significantly contribute to this.

Figure 1-3 systematically structures the constituting elements of the levelized cost of energy (LCOE) of a wind turbine system, which is basically the cost-yield ratio of wind energy. The yield site is mainly driven by the wind turbine characteristics – rotor diameter, hub height, blade profile, etc. – and the location characteristics, which are rather pre-set and cannot be influenced by operators in short-term. The cost-site, however, opens various possibilities for wind turbine operators to optimize the cost-yield-ratio of energy from wind turbines. At this point it is important to mention that the annual operation and maintenance cost ranges between 30 … 40 % of the overall annual costs of a wind turbine project (Bange et al. 2017). Annual capital costs are directly influenced by the direct wind turbine investment costs, the financing costs, and the overall service lifetime of the wind turbine. Considering the system distribution of the wind turbine investment costs, gearbox, rotor blades and the tower and supporting structure are the most capital-intensive subsystems.

To optimize the cost-yield ratio of wind energy from an operator's view, increasing the annual power output by reducing unplanned maintenance downtimes, lengthening the service life of the wind turbine while retaining a reasonable reliability level, and reducing the overall maintenance and repair cost are the main levers.

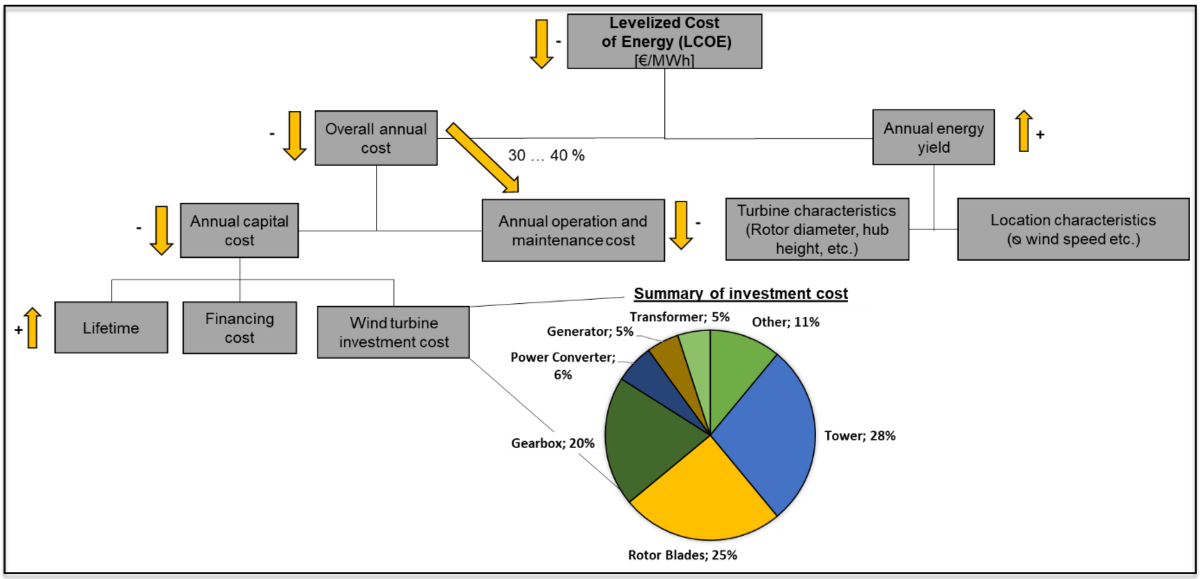


Figure 1-3: Constituting elements of the levelized cost of wind energy (Geiss 2014)

The employment of monitoring and inspection techniques within the operational phase is a basic key technology in outreach for these three goals. Continuous monitoring and inspection increases the knowledge of the operator of the system state, to define a cost-efficient operation and maintenance strategy.

As shown in Figure 1-4, Germany, as a leading European player in the wind energy sector, has currently installed around 27,780 wind energy systems onshore and 950 offshore systems. Global leader in installed wind energy capacity is China with 62.4 GW (2nd USA: 46.9 GW; 3rd Germany: 29.1 GW; 4th Spain: 21.7 GW), generating an enormous new business volume. A thorough overview of the global wind energy market is given in Geiss (2014).

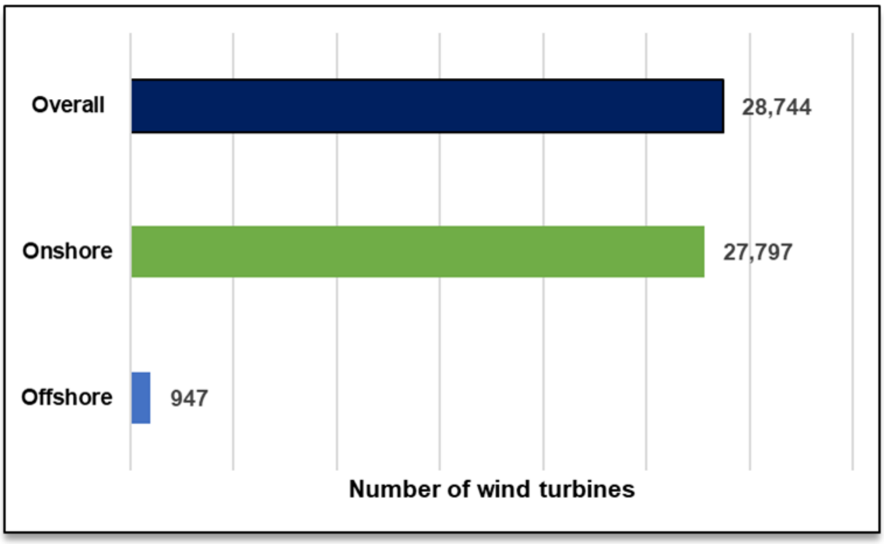


Figure 1-4: Number of installed wind energy systems in Germany – adapted from (Bange et al. 2017)

Due to strong political incentives starting with the German feed-in tariff regulation, a majority of the onshore systems was installed between the late 1990s and early 2000s (Bundesrat 10/5/1990). The conceptual design and funding policy is based on a service life of not more than 20 years. As shown in Figure 1-5, currently over 3,000 wind turbine systems already have exceeded their original designed service life of 20 years. A majority of the overall capacity of German wind energy installations is older than ten years – approx. 56 % - and already in its second half of service life. Similar age structures of the overall wind turbine capacity can be found all over Europe, especially in Spain, the UK and Denmark (Ziegler et al. 2018). However, in the upcoming ten years, focus on lifetime extension options as an economic optimization strategy will need to be laid for these wind turbines currently representing the lion's share of the installed capacity, to operate in a more and more competitive European energy market.

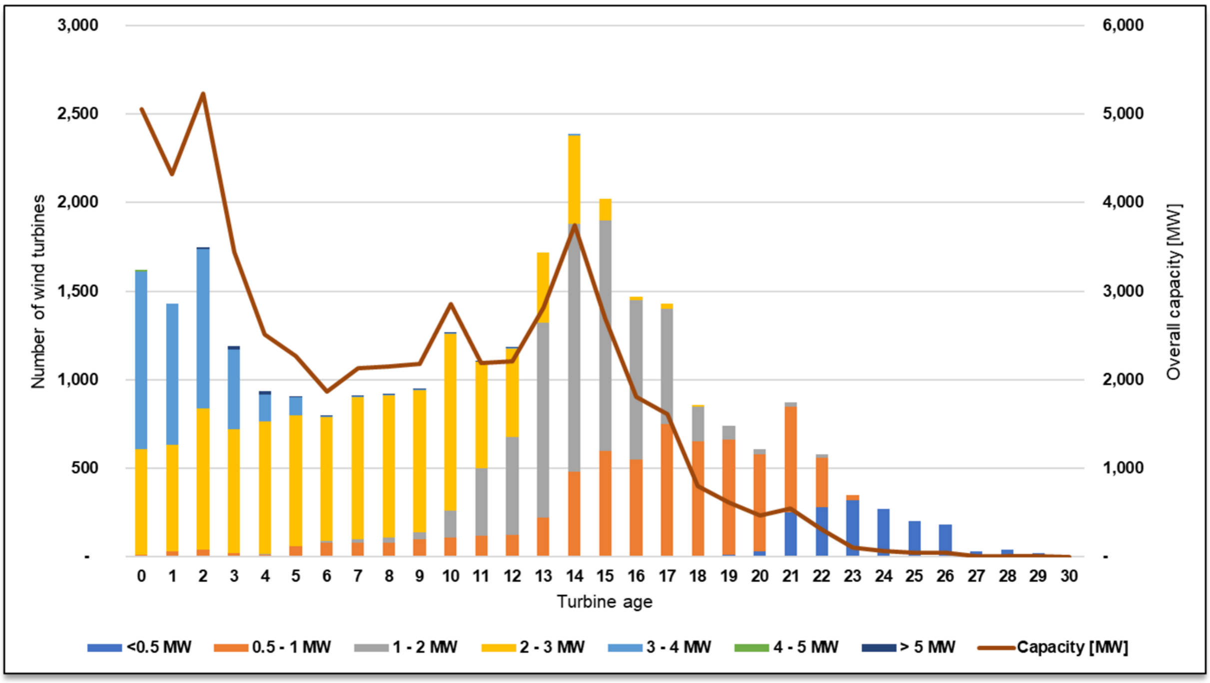


Figure 1-5: Age structure of the German wind energy capacity – adapted from (Bange et al. 2017)

Besides the drivetrain components, the supporting structure of a wind energy system binds a high amount of capital expenditures (CAPEX), on average between 20 to 30 % of the overall capital expenditures. During the service life of wind energy systems, the structural supporting structure is inherited with particular importance. While drive train, generator, and rotor blade systems already dispose over practically applicable monitoring systems, this is not the case for the structural supporting structure system of a wind turbine. Supporting structures carry all operational loads of mechanically highly dynamic wind turbine systems over 20 years and longer. Thus, supporting structures are highly loaded systems under the aspects of fatigue of materials and other mechanical and chemical deterioration processes. A service lifetime of 20 years can result in up to10^9 load cycles for a wind turbine supporting structure - Figure 4-63. However, from a technological, economical, and sustainable point of view it seems worthwhile to maintain the supporting structure of a wind turbine systems as long as safety and reliability levels can be fulfilled at reasonable cost, and replace, repair, or overhaul other main drive train and power converting components. Besides, current project costing modules in the wind energy sector pledge significant profitability advantages aiming for a lengthened service life time of wind turbines (Geiss 2014). Actual technical service life reserves of wind turbine supporting structures are currently unknown. However, industry experts state that in the recent history of wind turbine design philosophy the concept of safety factors was predominant, and they presume that after 20 years of operation, the majority of supporting structures will not have reached their designed resistance capacity (Luengo and Kolios 2015; Geiss 2013) – see also Figure 2-16. First scientific research approaches in the field have confirmed this (Loraux 2017). Evidentially, service life time extension is attracting more and more wind turbine manufacturers. Especially in Germany, moreover, possible installation sites of wind turbines from both legal and technological perspective – e.g. sonic ranges, construction heights, etc. - are used to their capacity. For the evaluation of remaining useful service life capacities, the industry needs lean and holistic approaches which consider the accuracy of judgement as well as the practicability and cost-benefit ratio of such analysis methodologies. To entirely recalculate existing wind turbines using high fidelity design tools, would result in six-digit expenses for wind turbine operators and show no proportionality to the expected results. Thus, the wind energy industry is in need for new holistic prognostic and health management valuation principles for wind turbine systems.

The structure of the thesis is aligned along core research questions, which will be introduced in the next chapter.

1.3 RESEARCH QUESTIONS

Wind turbines are probably the most dynamically stressed constructions we know in the art of engineering. Besides, in times of energy transition from conventional power to renewable power technologies, we rely on the operation of wind turbines on a macroeconomic level. Therefore, all parts of a wind turbine system must be subjected to quality management including design, manufacturing and especially operation and maintenance. On the system level this includes all main systems of a wind turbine plant – rotor blades, power train and especially the supporting structure, because it is one of the most capital-intensive and worth retaining parts of a wind turbine.

Nondestructive testing and structural health monitoring techniques can be applied to establish new efficient and sustainable maintenance strategies for wind turbine systems. The research focus in the framework of this thesis, is on the development of new maintenance strategies for wind turbines using combinations of inspections and monitoring techniques.

Existing maintenance strategies are investigated in a wider frame. Furthermore, a qualitative risk analysis determines the more critical parts of a wind turbine system.

State of the art NDT and SHM techniques are evaluated concerning their potential to contribute to quality control, conservation and sustainability of wind turbine systems. A combination of different NDT and SHM techniques is presumable the most successful approach to new inspection strategies. The main research questions (RQ) of this thesis are formulated in the following passage:

- **RQ 1:** *Which overall macro and micro economic role and importance can a holistic asset management concept for wind turbines have in the energy transition process?*

- **RQ 2:** *What is the status quo in wind turbine asset management and which requirements can be considered for a holistic asset management concept?*

- **RQ 3**: *Which sub-systems of a wind turbine system induce the most risk potential from an holistic asset management view point?*

- **RQ 4**: *What can a qualitative maintenance strategy decision framework look like?*

- **RQ 5**: *Which damage detection and data analysis techniques are most suitable for a holistic asset management concept for wind turbines?*

- **RQ 6:** *How should a holistic and integrated asset management concept for wind turbines be designed?*

- **RQ 7:** *Is it possible to establish relations between SCADA data and load measurements for wind turbine fatigue monitoring?*

- **RQ 8:** *Which concept is suitable for combining monitoring and inspection techniques in one holistic approach?*

- **RQ 9:** *Which data management concept is most suitable for a wind turbine life cycle file?*

1.4 CONCEPT OF THE THESIS

The presented thesis is structured into six main chapters studying the main research topic of a holistic approach to asset and maintenance management of wind turbines. The logical structure of the thesis follows an analytic approach in the first parts and chapters, whereas the second part of the thesis is a synthesis of the found results on a system level.

Chapter 1 gives an introduction on the macro economical perspective of wind energy's role in global climate change and the European – or especially German – efforts to perform an energy transition process from fossil and nuclear-powered energy conversion techniques to renewable energy systems and explains which decisive role asset management system and especially monitoring and inspection techniques play. Furthermore, the main research questions of the thesis are formulated and defined.

Chapter 2 is dedicated to the fundamentals of wind physics and wind turbine systems. Relevant stress and loading situations and relevant design load assumptions are presented. Lastly, current regulations on enhancing the service life time of wind turbine systems are introduced.

Chapter 3 deals with the basic principles of asset management, introduces the basic operative maintenance strategy concepts, and evaluates asset management approaches in related industries. Additionally, the research project *MISTRALWIND – Monitoring and Inspections of Structures at Large Wind Turbines*, which was initiated out of the doctoral thesis and contributed significantly to the findings, is presented.

Furthermore, **Chapter 4** is the main part of the thesis. The developed Integrated Asset Management System for Wind Turbines (IAMS-Wind) is designed, depicted, and analyzed. The paragraphs lead through the system design, over the interpretation and implementation of the system design, to a qualitative risk analysis of wind turbine systems, which defines critical parts in a wind turbine system. The risk categorization is core for the preliminary maintenance strategy decision procedure. Risk categorization and failure modes are linked with suitable monitoring and inspection techniques in an individually developed damage detection database. The core of the IAMS-Wind concept is represented by a multi-level condition and structural health monitoring module, which combines standard data analysis with high resolution sensor data from Structural health (SHM) and Condition monitoring systems (CMS). Finally, the approach presents a probabilistic approach to combine information from nondestructive testing techniques as deterioration control and update of fatigue design assumption which are used by monitoring systems to predict a remaining useful service life (RUL) for wind turbine structures.

Chapter 5 is dedicated to the discussion of the general effectiveness and practicability of the designed concept in the industry.

Chapter 6 summarizes the main findings and gives an outlook on rewarding future research topics.

2 WIND TURBINE SYSTEMS

Figure 2-1: Wind turbines as modern power plants (Siemens Gamesa Renewable Energy SA 2016)

When the wind of change blows, some people build walls, others build windmills.

Chinese Wisdom

2.1 THE PHYSICS OF WIND

Generally, wind can be described as directed movement of air masses. Source of this movement is the radiation of the sun, heating the earth's surface. The earth absorbs the radiation energy of the sun and emits parts thereof with a timewise difference into the atmosphere. The amount of absorbed radiation energy varies considerably over the earth's surface. The absorbed radiation energy undergoes daily, annual, and geographical variations. At equatorial zones surplus amounts of radiation heat is existent, which will be moved to the pole zones by macro climatic effects. This macro climatic transportation is realized by air movements to 80 % and by sea streams to 20 % (Quaschning 2015).

The differences in temperature, air density and air pressure in the atmosphere are core relevant for the basic physics of wind, because they result in the occurrence of areas of high and low air pressure. These areas seek for an energy equilibration through exchange of air masses – common wind. Due to the spherical shape of the earth, the tropic areas absorb much more radiation energy than the polar zones. Thus, a permanent exchange of air masses between the polar and tropical regions exists. Additionally, the *Coriolis*-force contributes to the orientation of the global winds. The *Coriolis*-force is caused by the earth's rotation and deflects the air masses in movement. *Coriolis*-forces occur in rotating reference systems, if masses move relative to the reference system. In the northern hemisphere the *Coriolis* force acts in flow direction to the left, in the southern hemisphere in flow direction right. From the poles to the equatorial zone, the *Coriolis*-force increases. A short overview of the earth's wind systems is given in Figure 2-2.

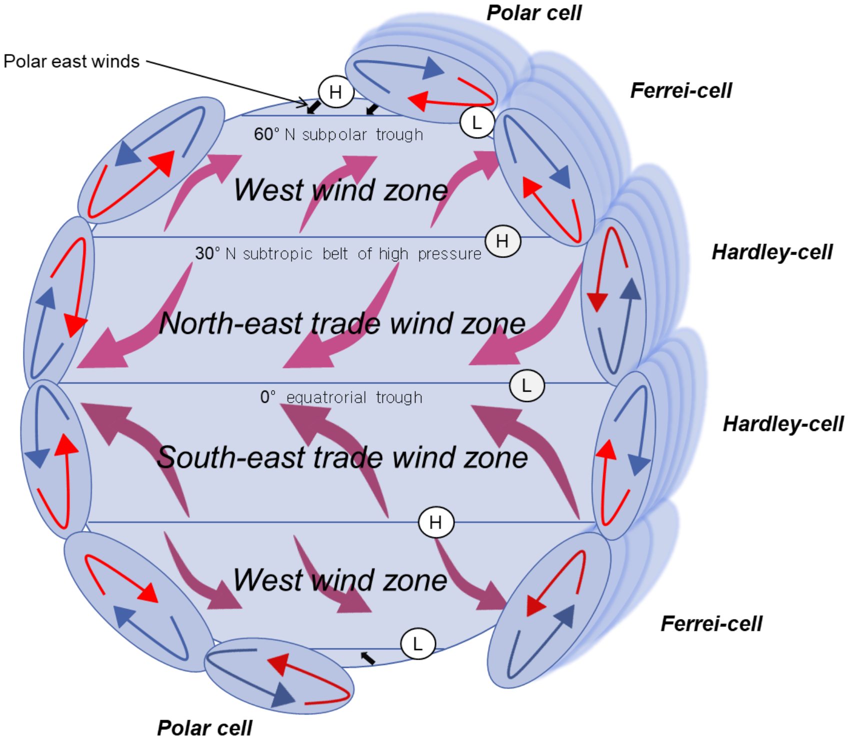


Figure 2-2: Global wind system – adapted from (Schönwiese 2013)

The global heat exchange movements take place in the geostrophic wind system in altitudes from 1,000 m to 10,000 m. Besides the *Coriolis*-forces, the geostrophic winds are subjected to compressive forces which act vertical to the direction of the *Coriolis*-forces. On a compensating distance of 1,000 km from the equatorial zone to the poles, the air pressure drops about 10 hPa (Rindelhardt 2012). Compared to direct solar radiation, wind systems have a low spatial variability. However, due to the physics of wind emergence, there exists a seasonal variation between winter and summer. In winter the difference in air pressure between the equatorial zone and the pole zones in the northern hemisphere is greater, therefore the movement of air masses is also increased.

Wind speeds increase with height above ground. As altitude increases, wind movements find less obstacles for a free flow. One way of mathematical description of this circumstance is the model of logarithmic boundary layers. The wind speeds can be determined in dependence of altitude and roughness length. Furthermore, the atmospheric stability must be considered to define wind speeds. The roughness length defines at which height above ground the wind speed will be slowed down to standstill – the greater the roughness length, the greater the influence on wind conditions at site. Additionally, the parameter d considers the offset of the boundary layer from ground, which can be caused due to additional obstacles. If the obstacles can be considered as far-flung, d can be set to zero. In practice, d can be estimated by taking 70 % of the obstacle height as d (Gasch et al. 2007).

$$v(h_2) = v(h_1) \cdot \frac{\ln(\frac{h_2 - d}{z_0})}{\ln(\frac{h_1 - d}{z_0})}$$

Equation 2-1

Table 2-1: Examples for different roughness length values (Quaschning 2015)

Roughness length z_0	**Surface**
0.0002 m	Open sea
0.005 m	Tide land
0.03 m	Grazing land
0.1 m	Agricultural area with low inventory
0.25 m	Agricultural area with high inventory
0.5 m	Landscape with trees and bushes
1 m	Forests, villages, suburbs
2 m	Urban area

Independence of wind speeds from altitude can be observed at altitudes of 1,000 m and higher. Air movements above 200 m above ground can be defined as geostrophic wind layers. Generally wind turbines are operated in the intersection between the *Ekman*- and *Prandtl- layer*. Figure 2-3 gives a generic overview of the logarithmic boundary layer model in the atmosphere.

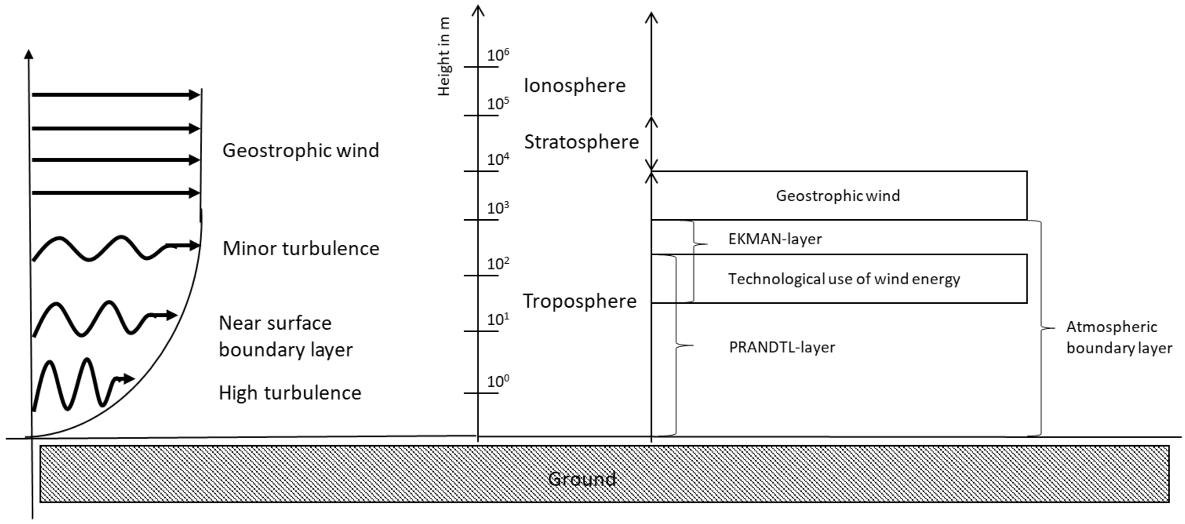


Figure 2-3: Logarithmic boundary layer model – adapted from (Burton et al. 2011)

Subordinate to the described global wind system, there are many local wind systems. The basic and most important wind systems will be described in the following passage.

Sea-land-breeze

During the day, air masses above land heat up more quickly than above sea, warm air masses ascend above land and drift as compensation movement above sea. There, the air masses cool down, sink and drift back on to land. At night this mechanism is reversed, because land cools quicker then water masses at sea. Thus, air masses rise at sea, drift in higher layers on to land, cool down, sink and drift again onto sea.

Mountain-valley-wind

South-facing mountain slopes absorb high amounts of solar radiation during daytime and heat up more quickly than valleys which remain in the shade. However, when the sun sets, spacious mountain slopes cool down more quickly than these valleys. During the day, air masses flow from the valley to the mountain slopes and vice versa during the night.

Down wind

If air masses impinge at mountain massifs, down winds result at lee side of the massif. A warm down wind e.g. is the so called *Foehn* in the alps. The *Bora* wind system at the Adriatic coast represents a cold down wind.

For weather observations wind speeds are measured at 10 m above ground following international standards. Considering reliable wind speed measurements for potential wind site assessments, the height-dependent wind speed course over a longer period of time is decisive (Schönwiese 2013). The default systems for measuring wind speeds for wind turbine site assessments are the vane anemometer and the ultrasonic anemometer. SODAR (acronym for: Sonic Detection and Ranging) and LIDAR (acronym for: Lightning Detection and Ranging) gain more and more importance. However especially LIDAR systems are comparatively expensive and therefore mainly used in research applications.

Besides wind speed, the turbulence intensity is an essential parameter for site estimations and loading of wind turbine systems. Figure 2-4 displays the spatial and temporal magnitude of the atmospheric phenomenon.

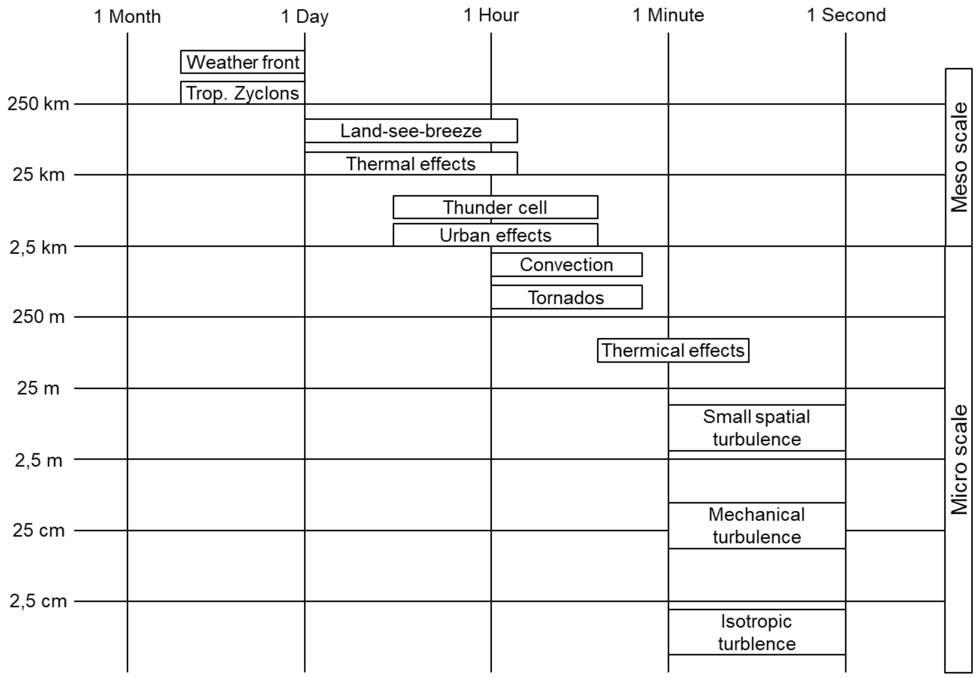


Figure 2-4: Spatial and timewise turbulence phenomena – adapted from (Burton et al. 2011)

Wind turbulence describes the temporal change of wind speed in a specific time frame smaller than ten minutes. Two main physical reasons can be identified – friction of the air flow on the earth's surface at low-lying obstacles, and thermal effects which deflect air masses in vertical directions due to changes in temperature and pressure. In reality, these effects often occur in combination, the turbulence of wind being a complex natural relation which cannot be described fully with deterministic notations (Burton et al. 2011).

Therefore, it is more practical to describe wind turbulence through a statistical approach, in which however turbulence stays a three-dimensional phenomenon.

$$I_{x,y,z} = \frac{\sigma_U}{\overline{U}}$$

Whereas:

- $I_{x,y,z}$ … Turbulence intensity [%]
- σ_U … Standard deviation of wind speed in specific time interval [m/s]
- U - Average wind speed in specific time interval [m/s]

Equation 2-2

In statistics, wind turbulence can be described as the standard deviation over the average wind speed in a specific interval of time. The distribution of wind speed changes resembles a standard normal distribution. However – due to the high dependency from specific site conditions – the peripheral areas deviate from a standard normal distribution. Thus, a standard normal distribution cannot be applied to forecast probabilities of high wind gusts. Figure 2-5 shows the measured turbulence intensity versus the wind speed in the first German offshore wind park alpha ventus as an example.

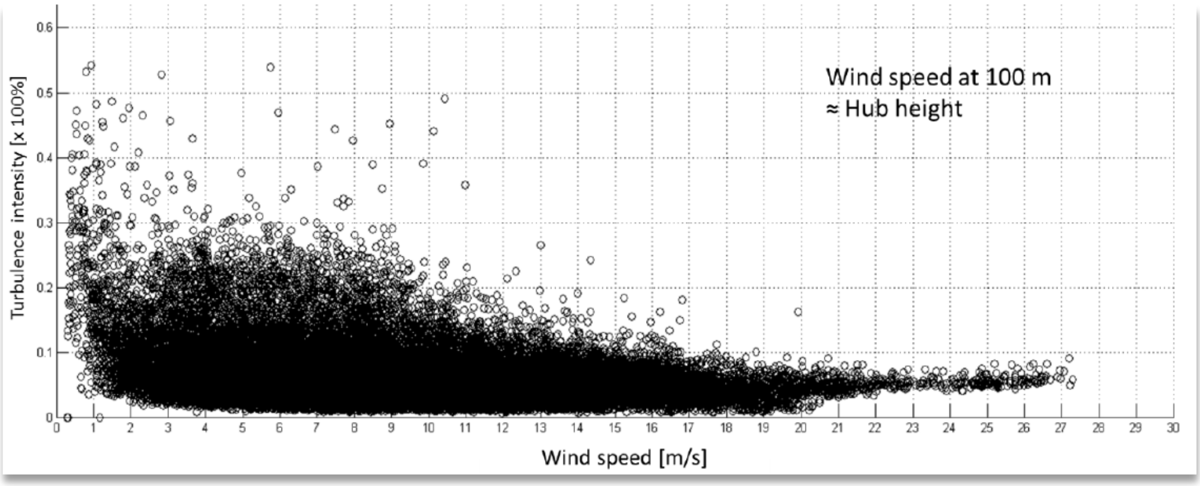


Figure 2-5: Turbulence intensity at the first German offshore wind park alpha ventus (Geiss 2013)

Differentiated significance describing wind conditions at specific locations can be enabled through specifically relevant distribution forms like the Weibull-distribution as well as the Rayleigh-distribution.

Weibull-distribution of wind speed v at a specific site is determined by a shape parameter k and a scale parameter a.

$$f_{WEIBULL}(v) = \frac{k}{a} \cdot (\frac{v}{a})^{k-1} \cdot \exp(-(\frac{v}{a})^{k})$$

Equation 2-3

Table 2-2 gives a short overview of example locations and their *Weibull*-parameters describing the local wind conditions (Quaschning 2015).

Table 2-2: Weibull-parameter and average wind speed in 10 m altitude of locations in Germany

Location	**k**	**a**	$\bar{v}$ **[m/s]**
Berlin	1.85	4.4	3.9
Hamburg	1.87	4.6	4.1
Köln	1.77	3.6	3.2
München	1.32	3.2	2.9
Nürnberg	1.36	2.9	2.7
Stuttgart	1.23	2.6	2.4

Hence, given the information of the average wind speed of a specific location one can determine the local wind speed distribution. Figure 2-6 displays the site characteristic of the research center Dresden-Rossendorf, by using a SODAR-station (Geiss 2012).

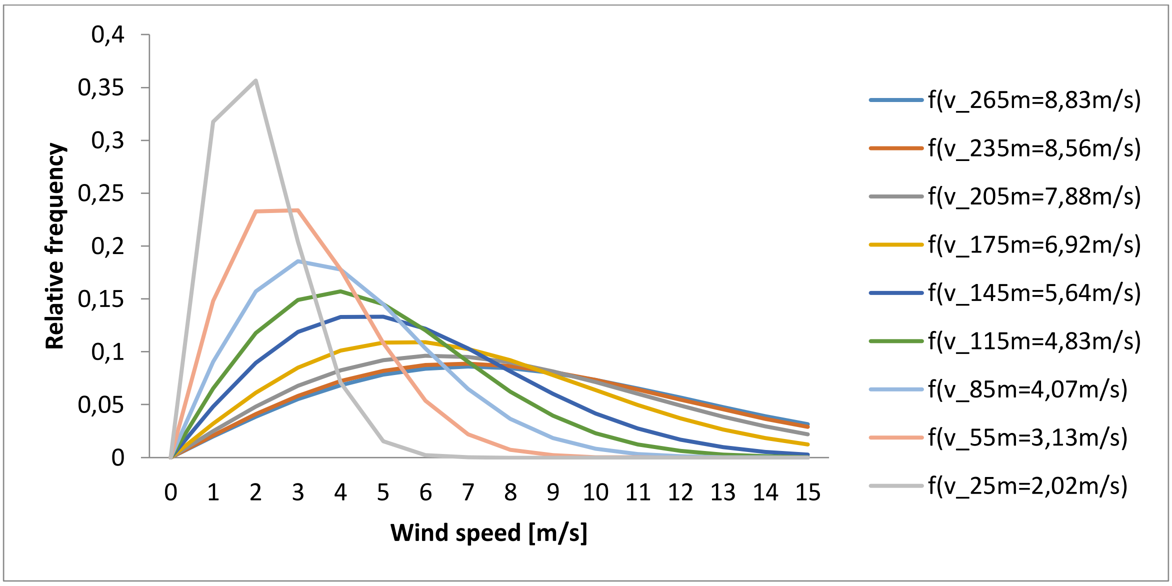


Figure 2-6: Wind speed distribution of the research centre Dresden-Rossendorf (Geiss 2012)

2.2 TECHNOLOGICAL DEVELOPMENT OF WIND TURBINES

The first historically known wind turbines were built in the 7th century BC in the orient, had a vertical axis of rotation and worked according to the principle of aerodynamic drag. Braided mats were attached to vertical wooden frames, which on one side were shadowed with a stone wall. The thus created asymmetry was the primary driving source capturing directed wind flow and using its drag to drive the rotational axis of the wooden frame. Those first wind turbine systems were primarily used to water dry plains. Only in the 12th AD were the first vertical axis wind turbine systems developed in the occident. The first design concept was the post wind mill. The design was based on a box-shaped mill house, which was mounted rotatable on a block. The concept of post wind mills spread in the Netherlands, France, and Germany to drive millstones. Later, the technical principle was also used to drain polders. Starting with the 19th century, the next technical evolution was realized on the American continent – the western mill. The impeller with a diameter of 3 to 5 meters integrated approximately twenty shovels made from sheet metal and was mounted rotatable on a lattice tower. The impeller was pivoted on the lattice tower able to rotate in the primary wind direction by steering of a wind vane. Until today western mills are deployed for drinking water supply and water supply of railway stations. Due to the automatic yaw system and storm deactivation, such systems can be operated autonomously.

Paul LaCour – professor at Askov Folk High School – was the first to study the use of wind turbines to transform kinetic wind energy into electric energy in 1891. His research lead to the development of the four-bladed LaCour-turbine operating with direct current. This system was especially valuable for the electricity supply of single farmsteads in Denmark (Bilau 1933).

The time after World War I was characterized by scientific penetration. By development and application of the actuator disc theory, *Betz* concluded in 1920 that wind turbines can deprive up to 59 % of the kinetic wind energy of free air mass flow (Betz 1926). He continued his findings with the blade element impulse theory, which represents a basic milestone in the development of design rules for wind turbine blades and blade profile geometries. Due to the outbreak of World War II and the relatively high cost of energy generation from wind, the technological development came to a standstill. With the reconstruction of a destroyed Europe after World War II and the growing awareness for sustainability and limitedness of natural resources, wind energy arose again. Driving forces were *Johannes Juul* in Denmark and professor *Hütter* at the University of Stuttgart. In Stuttgart *Hütter* developed the wind turbine W34 which was a technological milestone. The design comprised glass-fiber rotor blades, an electro-hydraulic pitch angle regulation of the rotor blades, and a synchronous generator. The rotor dynamic of the two-bladed wind turbine was damped applying a pendulum hub.

In the beginning of the 1960s, Europe was supported with cheap oil from the Middle East and sustainable energy was again losing its political relevance. After the two oil price shocks in 1973 and 1978, the aerospace industry in Germany and the USA rehabilitated the development of wind turbine systems in federally funded research projects which were both controversial and fruitful for the energy sector. NASA, MAN, and MBB failed with their modern concepts of wind turbines – Monopteros, GROWIAN, etc. – mainly due to technological difficulties. However, the Danish manufacturers in the agricultural machinery – Vestas, Bonus and Nordtank – developed their designs according to *Juuls*, with asynchronous machines, and followed the *Hütter* design in using glass-fiber reinforced blades, and finally had a break-through.

The introduction of federally funded feed-in tariffs in the early 1990s paved the way for an international wind turbine industry with multi mega watt wind turbines (Dörner 2009; Bilau 1933; Heymann 1995; Hütter and Armbruster 1963; Juuls 1964). The latest nuclear catastrophy at Fukushima in 2011 acted as a catalyzer for prosperous national and international policy programs to strongly foster energy from wind energy. The German “Energiewende” acts as a model project to economically redesign and decarbonize a historically grown energy system with renewable energy sources – energy from wind on- and offshore is a major pillar.

2.3 STRUCTURE OF A WIND TURBINE SYSTEM

Common for all wind turbine systems is the transformation of kinetic energy of moving air masses to mechanical rotation energy. The basic aerodynamic drive concepts can be subdivided into two main principles – drag resistance rotors and aerodynamic lift rotors.

Drag rotors have little importance, as modern wind turbine drive systems are based on aerodynamic lift concepts. The most significant differentiator in this group is the orientation of the rotor drive shaft. Lee rotors are mounted in air flow direction behind the tower; these can also be used for wind direction alignment. Luv rotors are successfully established today. Their aerodynamic rotor is mounted in air flow direction in front of the tower, bearing thus aerodynamic advantages in operation. However, the latter require a separate system for wind direction alignment. The following passages will focus on horizontal-axis modern grid-coupled wind turbine systems with the purpose of transforming kinetic wind energy into electrical energy. Gasch et al. (2007) and Hau (2006), give a comprehensive overview of other existing wind turbine drive concepts and purposes.

2.3.1 ROTOR SYSTEM

Modern rotors are three-bladed, showing dynamically optimized performance due to the uniform distribution of inertia and aerodynamic forces over the rotor circuit. Likewise, the optimized dynamic behavior of the rotor causes an even loading of all load bearing components in the following load path. One of the most important design criteria for rotor systems is the rotational speed of the rotor system. The mechanical performance of the rotor system P_{mech} is composed of the rotor torque M and the rotor speed n.

$$P_{mech} = M \cdot 2\pi \cdot n = M \cdot \Omega \quad [\frac{Nm}{s}]$$

Whereas:

- Ω … Angular frequency [1/s]

Equation 2-4

Furthermore, the tip speed ratio λ describes the ratio between the tip speed u and the speed of the free wind inflow v_1.

$$\lambda = 2\pi \cdot n \cdot \frac{R}{v_1} = \Omega \cdot \frac{R}{v_1} = \frac{u}{v_1} \quad [-]$$

Equation 2-5

At a given performance level, slow running turbines with a tip speed ratio $\lambda \approx 1$ have a high torque level. This can be beneficial for driving pumps for example. Modern wind turbine systems are designed with tip speed ratios of $\lambda \approx 5 \ldots 8$ and operate at higher rotor speed levels. For efficiency purposes, variable-speed concepts are of advantage, because wind turbines can be operated in a broad level of wind speeds at the optimal design tip speed ratio.

Wind speed rotor performance is based on two different aerodynamic concepts – stall and pitch. The aerodynamic stall system is older and simpler than the pitch system. The stall concept is based on aerodynamic rotor blade profiles which guarantee stall at a specific maximum wind speed to prevent overloads. To be able to actively control the stall behavior of the rotor blades, these are made with twistable blade tips. Stall-regulated wind turbines run with a constant rotor speed n and circumferential speed u, because the deployed generator concepts of asynchronous machines bind the wind turbines firmly to the grid frequency. The pitch concept is based on an active and independent blade alignment of all three rotor blades. Thus, every single rotor blade is equipped with an individual pitch drive. To regulate the aerodynamic forces, the pitch angle alignments of the rotor blades can be adjusted. If the wind turbine must stand still because of high wind speeds, grid requirements, or other reasons, all blades will be pitched to feather – the leading edges face the free wind inflow.

The power control of wind turbines is designed according to the fail-safe principle, and poses a second redundant mechanical breaking system which ensures that the wind turbine can be shut down in emergency – without external power supply.

On the material side, a major material applied for manufacturing is glass-fiber reinforce plastic (GFRP). Fiber inlays are distributed in the blade molds of both pressure and suction sides, and in the following manufacturing process polyester or epoxy resin is brought into the molds using vacuum infusion to imbue the fiber inlays. Some manufacturers have established the so-called sandwich construction, in which the outer and inner fiber inlay is separated with a balsa wood layer. By courtesy of a defined temperature increase the resin is hardened, then the suction and pressure sides are agglutinated. Both are individual components in large scale with up to 80 m in length. These steps are predominantly performed in manual work, manufacturing tolerances in centimeter ranges are thus unfortunately normality. To ensure structural stability, the rotor blades are foamed and equipped with webs and spars in GFRP. Finally, the blades are laminated with an erosion coating, protecting the blade structure from environmental influences. The force transmission from the rotor blades to the rotor hub is realized with firmly laminated bolts. Figure 2-7 provides a generic overview of the rotor blade construction.

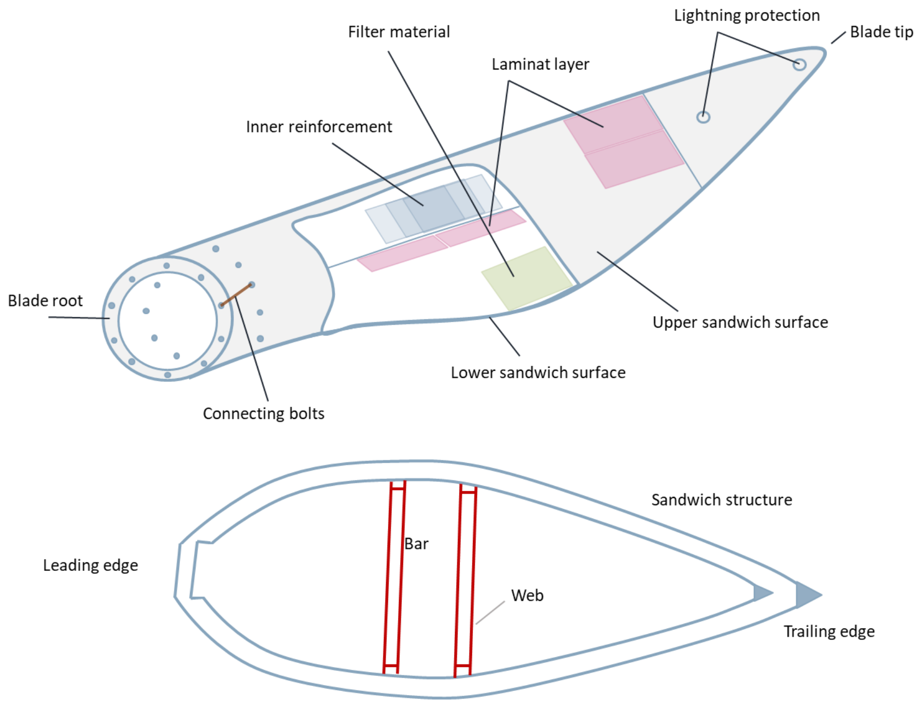


Figure 2-7: Generic rotor blade construction

Rotor blade constructions applying carbon-fiber materials will gain in importance in the future. Carbon-fiber technology is more cost-intensive on the material side compared to GFRP. However, carbon-fiber rotor blades can reach a higher level in specific material resistance and fatigue strength. Furthermore, carbon-fiber blade designs show a significantly improved weight to strength relation compared to GFRP constructions. For future large-scale rotor blades, applying carbon-fibers will be a key technology.

2.3.2 DRIVE TRAIN SYSTEM

The drive train system of wind energy plants represents a central sub system, which provides the generator system with the induced rotational energy from the rotor system in adequate form to transform kinetic wind energy into electric energy. Generally, drive train systems can be subdivided into four main drive train concepts on the machine carrier.

Integrated drive train

In this design, rotor bearing, gearbox, and generator are grouped. The gearbox applied in this design type is a special manufacture, because it integrates the rotor bearing and its large operational loads. Changing a gearbox unit without a complete disassembly of the machine-carrier is not possible. However, the compact design is an advantage in transport.

Dissolved drive train

As opposed to the integrated drive train concept, every single function of power transmission is built in separate in this design. An independent rotor bearing unit transmits the kinetic energy to a low-speed shaft which is connected to a separate gearbox unit. The outgoing high-speed shaft is connected to the generator unit. High accessibility and maintainability are two main advantages which this concept bears for operation. However, damage risks due to alignments errors exist. This concept is displayed in Figure 2-8.

Partly integrated drive train

This construction concept combines the integrated concept with the dissolved concept. The concept is based on a three-point bearing. The anterior rotor bearing transmits all inertia and axial loads from the rotor system. The kinetic energy is then transmitted over a low-speed shaft to the gearbox unit. The drive train is supported with two torque arms with elastomeric bearings.

Direct drive train concept

Electrical machines with a high number of poles and a large rotor diameter are applied in this concept. Due to the high circumferential speed, the velocities in the head gap are high enough to make gearbox transmission onto a high-speed shaft unnecessary. Rotor hub and generator are directly connected and pivoted together on a kingpin.

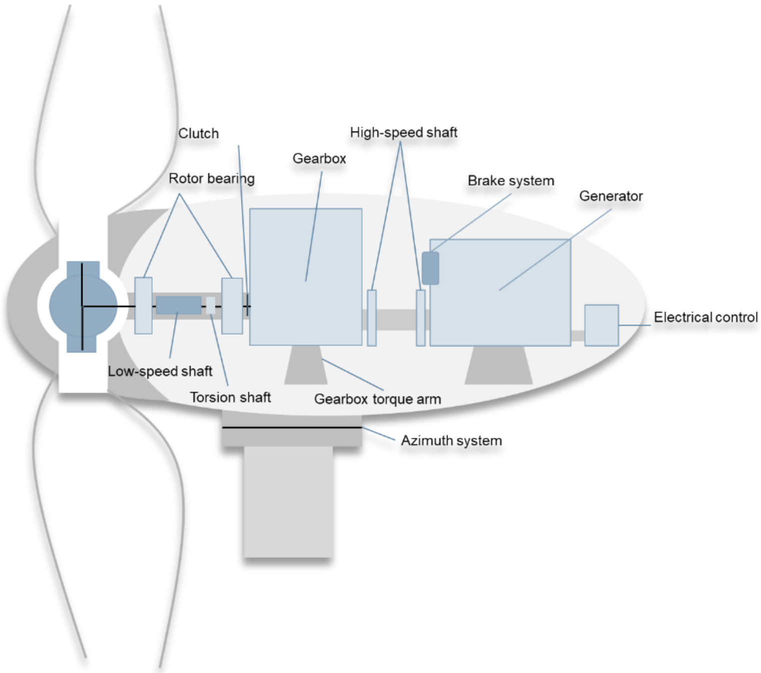


Figure 2-8: Dissolved drive train

The machine carriers are mostly built in cast iron or welded constructions. With increasing plant capacity, machine carriers must be constructed in parts, due to component weights. Horizontal-axis wind turbine gearbox units are mostly spur gearings or planetary gearings. Spur gears are applied in wind turbines in lower capacity classes (< 500 kW). Planetary gears can achieve higher degrees of efficiency at lower acoustic emissions and are therefore especially suitable for wind turbines of higher capacity classes (> 500 kW). A key criterion for the required input shaft speed for generator systems is the specific pole amount of the applied generator. Early stall turbine concepts with grid-connected asynchronous machines used four, six, or eight pole machines. With a common 50 Hz grid frequency, the required rotor speed input is thus 1,500, 1,000, or 750 rpm. Generator concepts combined with variable speed drive trains have the same requirements according to the input shaft speed. Only the high pole amount of separately and permanently excited synchronous machines enable drive train operations without a gearbox unit.

2.3.3 SUPPORTING STRUCTURE SYSTEM

In comparison to other similar tall and high structures, loading of the wind turbine tower due to its own dead loads is relatively low. By far the most structural loading is due to bending loads induced by wind inflow. Separate design guidelines are in place in Germany for the tower and fundament (Deutsches Institut für Bautechnik - DIBt 2012) . Besides the special dynamic effects of wind turbines, the guidelines also factor in the specific site classifications when it comes to wind loading. Extreme load cases are deployed to verify the steadfastness of the supporting structure. Structural durability load cases are deployed to verify the fatigue strength. Structural durability aspects are driving design criteria for supporting structure constructions for wind turbines. Within the presently planned design life time of 20 years one can assume up to 10^9 load cycles in operation. In this magnitude of load cycle ranges there are limited other and comparable structures in operation. Bridge structures experience 10^7 load cycles within their assumed service life Figure 4-63. To counter those extreme fatigue load conditions, a variety of construction designs for wind turbine supporting structures are usable (Burton et al. 2011). The most important construction methods are displayed in Figure 2-9 .

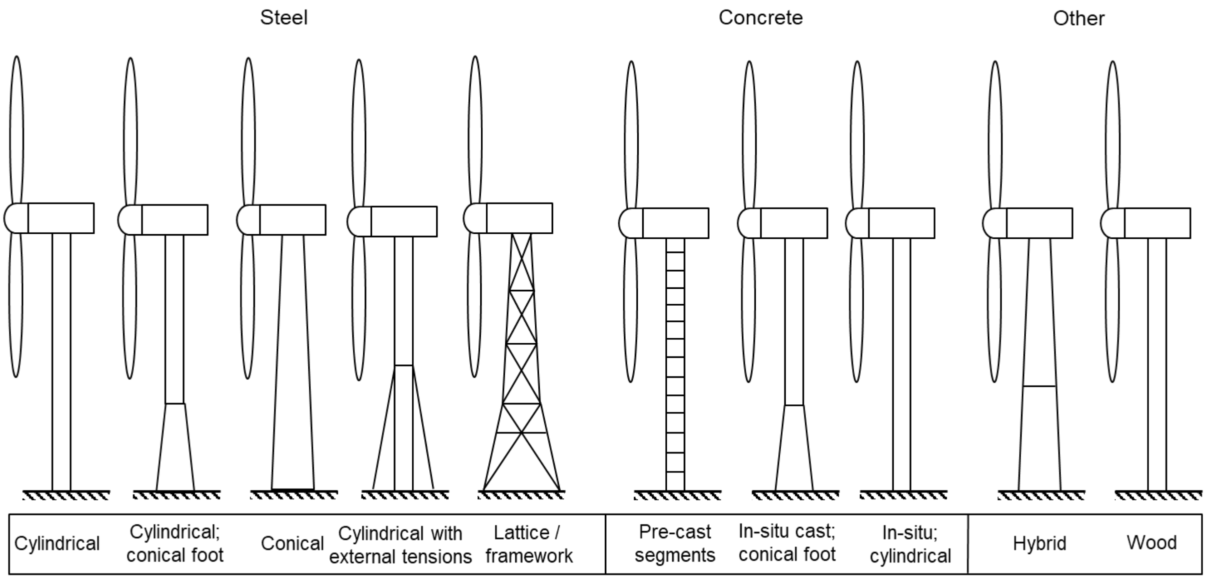


Figure 2-9: Construction methods of wind turbine supporting structures

<u>Tubular steel tower</u>

The most widespread construction type of wind turbine support structures is the tubular steel tower. The construction concept is mostly built from five sections, each with a specific length of up to 30 m and wall thicknesses between 20 and 50 mm. A common construction material is structural steel S235. In case of constructions with higher demand, structural steel S355 is deployed. For connecting elements – such as flanches – and those section which are casted into the fundament, the industry deploys steel types of higher resistance levels. L-shaped flanches connect the single tower sections with bolted connections. This ensures a relatively fast erection of the tower segments at site. The single segments are built from tubular-bended sections which are welded together, whereas the diameter of the single segments decreases with height – in such way the tower takes a conical form. The conical form represents an optimized relationship between material usage and stiffness demands, because the tower bending moments decrease from the tower top section to the fundament section. Furthermore, this shape assures tower clearance in the upper tower sections when rotor blades pass during operation. Usually there is a doorway in the lower section to enter the tower. Due to the already described high bending loads in the lower tower section, doorways are often reinforced in the fringe region. For regular maintenance and inspection activities in the tower sections, a vertical ladder is provided inside the tower. Modern wind turbines often have installed technical escalator systems in the tower to ease maintenance and inspection activities in heights. Intermediate platforms are often integrated at the end of each tower sections from where the connection flanches can be reached and serve as intermediate service stations in maintenance and inspection missions. However, those service platforms do not increase the structural stiffness of the tower and are not part of the main load path in tower operations. When it comes to economics in construction design and material deployment, classic tubular steel towers become uneconomical at heights surpassing 120 m. The maximum diameter to transport segments in Germany on public roads is limited to 4.30 meters. To build a tower with 100 m in height, engineers would have to deploy a wall thickness of 55 mm to guarantee sufficient structural resistance (Gasch et al. 2007).

Lattice steel tower

Lattice and framework towers represent an alternative construction type. With similar structural resistance and stiffness levels, material deployment is 30 … 40 % less compared to the classic tubular steel tower with the same height. Moreover, lattice tower concepts show advantages in transportability. However, more important for operational aspects of the turbine tower, lattice towers aerodynamically perform better than massive tubular steel towers and cause less disruption of free air flow of the rotor blades. On the downside, erection and maintenance tasks are much more extensive deploying a lattice tower concept. The high amount of individual parts and connecting elements reveal themselves as time and cost intensive. Not least because of those matters, lattice and framework concepts have not established in the industry.

Concrete towers

In Germany concrete towers played a subordinate role for a long time. Normally they are built in in-situ concrete or in precast concrete segments. The former methods ensure high advantages in transportability. However, in-situ casting consumes a surplus amount of time, which must be considered. Furthermore, site planning can be more difficult and quality aspects of the in-situ cast are extremely dependent on the on-site conditions, thus difficult to control and standardize. Considering this aspect, deploying pre-cast concrete elements bears advantages, valuable time on-site while tower construction can be optimized, and manufacturing processes can be optimally performed, controlled, and standardized in a defined environment. In practice, manufacturers often build short elements to minimize transportation issues of the pre-casted elements.

Both in-situ casted and pre-casted construction concepts can be embodied with prestressing steel to pre-stressed concrete towers. Therefore, tendons made of high-grade steel are placed along the vertical axis of the tower, which are tensioned with external forces and induce compressive stress over the entire concrete structure. This concept is common in bridge constructions and enables a higher level of stiffness and resistance of the whole structure by compressing the concrete cross-section. Depending on the specific construction, the tendons can be placed inside of the concrete cross-section or along the tower wall on the tower inside, centric free swinging or led along panels.

Hybrid tower structure

To achieve the necessary rigidity of modern onshore wind turbines with hub heights above 120 m and suppress resonance frequencies induced by the rotor, the lower tower part must have a very large diameter. Besides material cost, transportation of such big steel parts in one piece is a difficult logistic problem. The hybrid tower concept combines the advantages of both steel and pre-stressed concrete towers and represents an economical system and logistically optimized combination of concrete and steel. Hybrid towers comprise a pre-stressed concrete part up to approx. 2/3 of the tower height. This part bears the top steel part sections. The concrete part can be produced on-site or be pre-fabricated in shell modules.

Foundations

The type and size of the tower foundation is dependent on the geotechnical conditions of the respective site, the turbine capacity, and the tower type. The soil on which a wind turbine is operated needs sufficient bearing capacity. An adequate ground assessment is of basic importance to design the specific foundations for a specific site. If the soil has sufficient bearing capacity, the operating wind turbine loads can be transferred into the ground with a spread footing concept. If the bearing capacity is not sufficient, pilling is required to increase the load bearing capacity. The piles support the footing and transfer operational loads to a more rigid ground level – e.g. the bedrock. Foundation of the tower structure in onshore areas is commonly performed with flat foundations. All tower concepts – except the lattice tower concept – are erected on a single footing. Because the grounding of lattice tower must be comparatively wide, each leg of a lattice tower is founded on a single footing.

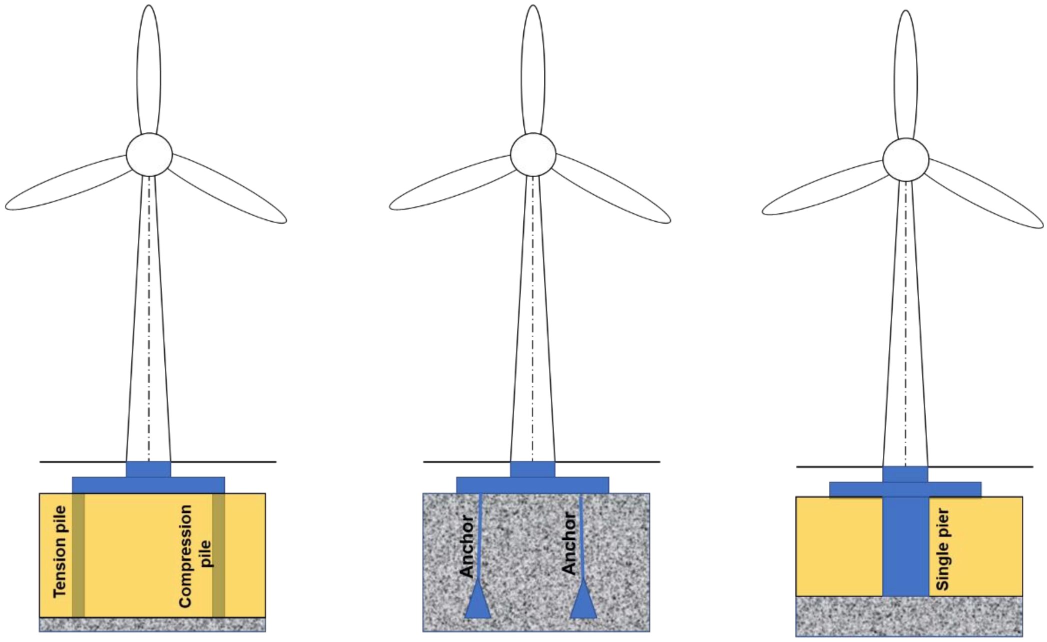


Figure 2-10: Different foundation types – a) spread footing supported by piles, b) spread footing anchored to the bedrock, c) footing supported by single pier

2.4 STRESS AND LOADING OF A WIND TURBINE SYSTEM

Assigning the principle of linear momentum according to Newton, one can derive the thrust force of a control surface which is flowed through. First, the power of wind and other basic physical dimensions have to be introduced (Hering et al. 2016).

The kinetic energy E_{kin} of a fluid with mass m and velocity v is defined along:

$$E_{kin} = \frac{1}{2} \cdot m \cdot v^2$$

Equation 2-6

For the air mass flow $\dot{m}$ with density ρ and the velocity v onto the control surface A_R holds:

$$\dot{m} = \rho \cdot A_R \cdot \frac{dx}{dt} = \rho \cdot A_R \cdot v$$

Equation 2-7

Therefore, one can conclude for an undisturbed and continuous air flow in front of the rotor plane:

$$\dot{E} = \frac{1}{2} \cdot \dot{m} \cdot v = \frac{1}{2} \cdot \rho \cdot A_R \cdot v_1^3$$

Equation 2-8

The power of wind on a control surface grows cubical in relation to the wind speed.

According to *Betz* it will be assumed a laminar air flow which is facing the rotor diameter of a wind turbine, flowing through the rotor diameter and will be decelerated far behind the rotor diameter. Due to mass preservation reasons the air flows generates a widened flow tube behind the rotor plane (Schade and Kameier 2013).

$$\rho \cdot v_1 \cdot A_{R,1} = \rho \cdot v_2 \cdot A_{R,2} = \rho \cdot v_3 \cdot A_{R,3} = \dot{m}$$

$$A_{R,1} \leq A_{R,2} < A_{R,3}$$

Whereas:

- $\rho \cdot v_1 \cdot A_{R,1}$ … air mass flow in front of rotor plane
- $\rho \cdot v_2 \cdot A_{R,2}$ … air mass flow in rotor plane
- $\rho \cdot v_3 \cdot A_{R,3}$ … air mass flow behind rotor plane

Equation 2-9

Due to a negligibly small pressure variation, pressure dimensions can be assumed as constant. The extracted kinetic energy from the wind flow results from the difference between the kinetic wind energy in front and behind the rotor plane:

$$\dot{E}_{ext} = \frac{1}{2} \cdot \dot{m} \cdot (v_1^2 - v_3^2)$$

Equation 2-10

And it follows:

$$\dot{E}_{ext} = \frac{1}{2} \cdot \rho \cdot A_R \cdot v_1^3 \cdot c_p$$

Equation 2-11

According to Betz one can also describe the extracted wind energy in dependence of the available wind power and the power coefficient. The power coefficient c_P is dependent on the ratio between outgoing and incoming air speed.

$$c_P = \frac{1}{2} \cdot (1 + {}^{v_3}/_{v_1}) \cdot (1 - ({}^{v_3}/_{v_1})^2)$$

Equation 2-12

Theoretically the maximum reachable power coefficient is $c_{P,max} = {}^{16}/_{27} \approx 0.59$. This would mean that the optimum ratio between outgoing and incoming air speed is reached, if the incoming wind speed is decelerated to a third of the initial air speed. From this it also becomes evident that an optimal wind turbine concept can extract a maximum of 60 % of the kinetic energy of free wind inflow.

According to the principle of linear momentum considering the wind thrust forces F_S it follows:

$$F_S = \dot{m} \cdot (v_1 - v_3) = \rho \cdot A_R \cdot \frac{v_1 + v_3}{2} \cdot (v_1 - v_3)$$

Equation 2-13

With $v_3 = {}^{1}/_{3}\, v_1$ and the thrust coefficient $c_S = {}^{8}/_{9}$ it follows for F_S (Gasch et al. 2007):

$$F_S = c_S \cdot (\frac{1}{2} \cdot \rho \cdot v_1^2) \cdot A_R$$

Equation 2-14

The dynamic pressure of the wind thrust onto the rotor plane A is expressed in brackets in the equation above. It follows that the thrust force of wind grows in square with the incoming wind speed.

Alternatively, one can also deduce the wind thrust equation deploying an energetic approach. Hereto, the energy balance of fluid mechanics according to Bernoulli has to be deployed (Schade and Kameier 2013).

Load causes of wind turbines can be categorized in the following core root causes:

- Loads induced due to aerodynamic forces
- Loads induced due to gravitational forces
- Loads induced due to inertia forces
- Loads induced due to operational situation, such as braking actions, azimuth movements, pitch movements or grid outages

Figure 2-11 graphically summarizes the load root causes of wind turbines according to their timewise character.

Origin / Time behavior	Force typ	Origin	Operating status
Quasi-static	Gravitational force, centrifugal force, average thrust	Gravitational force, centrifugal force, average thrust	Standard operation
Periodic	Mass imbalance, aerodynamic forces	Mass imbalance, tower effects, flow inclination, blade passage	Standard operation, disturbances
Stochastic	Aerodynamic and hydrodynamic forces	Wind turbulence, sea disturbance, earthquake	Standard operation
Transient	Braking loads, frictional loads, aerodynamics	Plant stops, azimuth, movements	Manouvre disturbances, extreme conditions

Figure 2-11: Load situations of wind energy turbines – adapted from (Gasch et al. 2007)

In real operating conditions a wind turbine always experiences a combination of all described load situations and causes. The relevant wind turbine design guidelines - IEC 61400 - configure sound load cases which combine the specific plant loads with external load conditions. The design load cases consider normal and extreme external conditions, e.g. a 50-year extreme gust, as well as normal and extreme plant conditions. In principal, design guidelines of wind turbines consider normal wind conditions and normal plant conditions, normal wind conditions and extreme plant conditions, and extreme wind conditions and normal plant conditions. The combination of extreme plant conditions and extreme external conditions is not considered in the design guidelines so far. This assumes that such a situation would occur extremely seldom and that these conditions are not correlative to each other.

The operational loads are introduced on the rotor system and are transferred to the whole plant structure. Maximum blade loads occur theoretically when the wind inflow direction is perpendicular to the rotor plane. In this load situation, the rotor blades have the highest air resistance. A more common maximum load situation is represented in situations when the rotor blades have the highest lift forces; this is usually the case for angles of inflow between 12° … 16° (Burton et al. 2011).

Operational loads of wind turbines have deterministic and stochastic load components. A uniform wind inflow represents a deterministic load component. Such load situations are determinable explicitly and with a small number of parameters. E.g. such a load situation is dependent on the hub height, the wind speed, the rotor speed, and the wind shear. Other deterministic load components are all gravitational and inertia loading situations. The gravitational loading is mainly dependent on the azimuth angle and the load distribution along the rotor blade. Inertia loads can be caused due to wind turbulences inter alia and are therefore both deterministic and stochastic in nature. Stochastic load components integrate all fluctuating and transient load situations.

According to the total loads of the turbine structure, the blade loads cannot be regarded as isolated. No turbine tower structure can be considered optimally stiff and therefore all fluctuating loads of the rotor system will be transferred to the tower structure. Mainly the thrust force of wind results in a global bending moment in wind direction at the tower root. And vice versa tower dynamics also influence the blade dynamics and cause the wind turbine to be an integrated dynamic system.

2.4.1 DESIGN GUIDELINES OF WIND TURBINES

In Europe, the first standardization processes for wind turbines began in the 1980s. Today decisive standards and guidelines in the wind industry are provided by Det Norske Veritas Germanischer Lloyd (DNV GL) (DNV GL AS 2016a). In the early wind industry days, the company – rooted in the offshore and marine sector - acted as a pioneering certification body for wind turbines (DNV GL AS 2016b). In Germany the guidelines provided by the German Institute for Building Technology - Deutsches Institut für Bautechnik (DIBt) - are also essential for the design and certification of supporting structures of onshore wind turbines. Concerning the offshore sector, the Federal Maritime and Hydrographic Agency in Germany - Bundesamt für Seeschiffahrt und Hydrographie (BSH) - provides guidance for the design and erection of offshore supporting structures on German territory (Bundesamt für Seeschiffahrt und Hydrographie - BSH 2015). Other decisive standards for wind turbine systems on European level are the Dutch standards (NEN 2016), the Danish standards (Dansk Standard - DS 2016), and the British standards (The British Standard Institution - BSI 2016). On international level standards and guidelines are framed, homogenized, and reviewed by the International Electrotechnical Commission (IEC) – Technical Committee 88 (TC88) (International Electrotechnical Commission - IEC 2016).

Particularly relevant IEC-Design codes for wind turbines on international level are:

- IEC 61400-1: Wind turbines – Part 1: Design requirements
- IEC 61400-3: Wind turbines – Part 3: Design requirements for offshore wind turbines
- IEC 61400-13: Wind turbines – Part 13: Measurement of mechanical loads
- IEC 61400-22: Wind turbines – Part 22: Conformity testing and certification
- IEC 61400-25 Wind turbines – Part 1 … 6: Communications for monitoring and control of wind power plants

Furthermore, the IEC-Design codes classify wind turbines in four different wind turbine classes according to the wind load characteristics of the respective sites, as shown in Table 2-3.

Table 2-3: IEC Wind turbine classes

	I High wind	II Medium wind	III Low wind	IV Very low wind
Reference wind speed	50 m/s	42.5 m/s	37.5 m/s	30 m/s
Max. annual average wind speed	10 m/s	8.5 m/s	7.5 m/s	6 m/s
50-year return gust	70 m/s	59.5 m/s	52.5 m/s	42 m/s
1-year return gust	52.5 m/s	44.6 m/s	39.4 m/s	31.5 m/s

2.4.2 DESIGN AND FATIGUE LOADING OF A WIND TURBINE STRUCTURE

Generally, the design of wind turbine structures can be subdivided into the following categories:

- Dynamic design
- Fatigue design
- Ultimate limit state design
- Crack width limitation design

Wind turbine tower designs follow already existing design specifications for tower-type structures, e.g. DIN 4133 for steel chimneys. Wind turbine decisive standards are aligned along the wind loading conditions of the planned wind turbine site. International and national standards differ with respect to load case definitions and partial safety factors.

Extreme and operational loads are calculated applying aeroelastic simulation codes (Flex 5, Bladed, etc.). The main influencing parameters are:

- Turbulence and wind field model acting on the rotor plane and the tower structure
- Dynamic behavior of the overall system of foundation, tower, rotor blades, and machinery components
- Aerodynamic influences
- Set-up of the wind-turbine controller
- Stiffness of the supporting structure

The respective eigenmodes of a tower structure are of crucial importance for the overall dynamics and are defined in the design phase. Especially the first eigenmode is in focus. The tower structure experiences different dynamic excitations during operation. Existing mass imbalances of the rotor blades lead to a so called 1p-excitation, which revolves with the rotor speed. Furthermore, so called 3p-excitations result from the rotor blade passing the tower. Every time one of the rotor blades passes the tower, the wind flow stalls and results in an abrupt decrease in uplift. On three-bladed wind turbines this dynamic excitation revolves with triple the rotor speed. Additional excitation frequencies are integer multiples of the rotor rotational speed; however, these are of minor importance for the overall dynamics. The closer the tower eigenmodes are to the excitation frequencies, the higher is the stress on the whole system. Therefore, the first eigenmode of towers must be at least 10 % above the 1p excitation frequency. Generally, wind turbine structures are weakly damped systems. The logarithmic damping factor is normally below 0.04. Therefore, excitation frequencies near the eigenmodes will result in dangerous super-elevations (Burton et al. 2011).

Determined parameters for tower constructions are the mass of the nacelle, the mass of the rotor, and the desired hub height. Thus, there are only few constructional influencing parameters. One is the variation of the prorated lengths of the concrete and steel part. Normally a larger amount of concrete increases the structural stiffness. Increasing the amount of steel lowers the structural stiffness. Geometrical influencing factors are the structural diameter and the wall thickness. Variations in wall thickness influence the stiffness, but also increase the tower mass, which in turn compensates the eigenmode effects. If it is not possible – for constructional reasons – to settle the tower's eigenfrequencies outside the 1p or 3p excitations in the dynamic tower operation, some rotational speed areas of the rotor must be omitted or specifically monitored. Another dynamic design influencing factor is the E-modulus of the chosen concrete. Generally, the E-modulus of the concrete part must be adjusted to the E-modulus of the steel part (Grünberg and Göhlmann 2013). If necessary, the concrete recipe is analyzed under laboratory conditions. Furthermore, the dynamic torsional spring effects of the chosen foundation type must be considered. Figure 2-12 displays the excitation circumstances graphically.

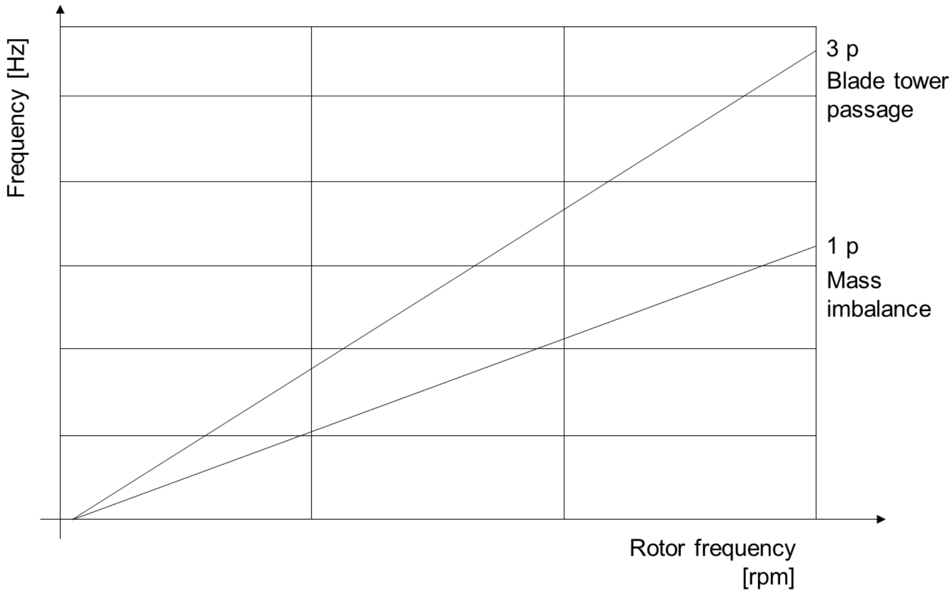


Figure 2-12: Dynamic tower excitations

Load calculations and verification analysis of the tower structure can be based on:

- Time-series
- Markov- or *Rainflow*-Matrices
- Terrace collectives
- Damage Equivalent Loads (DEL)

A basic description of the *Rainflow* algorithm can be found in Downing and Socie (1982). Sutherland described the application in use for wind turbine structures (Sutherland 1999). The concept of damage equivalent loads gives an explicit description of the damage potential of a specific load cycle. One advantage of applying DEL approaches is the comparability of different load situations, irrelevant if the load data comes from measurements or simulations.

The damage equivalent load is defined as a single load amplitude, which – given the total number of load cycles at a given frequency – induces the same damage as the sum of all load cycles counted with the *Rainflow* algorithm and their respective load amplitude.

Described in a mathematical manner, the damage equivalent load can be defined as the weighted average of the amplitudes from the *Rainflow* count. The weighting exponent m is material specific.

$$F_{eq} = \left(\frac{\sum F_i^{m_W} \cdot n_i}{n_{eq}}\right)^{\frac{1}{m_W}}$$

Equation 2-15

To calculate damage equivalent loads it is necessary to define the amount of reference load cycles n_{eq}. The amount of reference load cycles is directly dependent on the load cycle type under analysis and should therefore be representative for the respective load cycle type. In wind turbine applications the reference frequency of 1 Hz – near the structural eigenfrequency – is established (Haibach 2006).

However, as the approach is based on the theory of linear damage accumulation, sequence effects of loads on the fatigue evolution of a structure are not considered and a linear relation of the amount of load cycles and the fatigue state is assumed. It is therefore important to note that the approach is practical for load analysis but remains a descriptive approach.

Despite being the major limitation for the design of wind turbines, fatigue is rarely the cause of a complete failure of the tower. Such dramatic events remain exceptional and are the result of negligence during the assembly. In almost every reported case of a tower failure (not resulting from a blade failure), the failure arises from the fatigue of the high strength bolts connecting the tower sections (Loraux 2017).

Loraux studied the long-time fatigue behavior of a wind turbine structure in his dissertation project. One conclusion was that few extreme events – such as storms or emergency shut downs – contribute the lion's share to the overall fatigue damage (Loraux 2017). Figure 2-13 displays the overall damage contribution in a two-year monitoring period in a -log(D) scale. Loraux shows that a few short extreme events contribute to approximately 50 % of the overall damage.

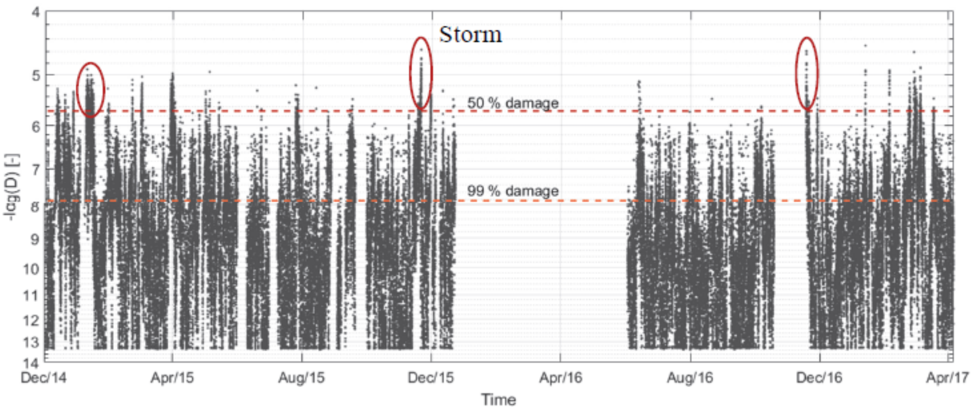


Figure 2-13: Overall damage contribution over a two year monitoring period (Loraux 2017)

Figure 2-14 reinforces this statement, while showing the percentage distribution of operational time, damage accumulation, and relative damage over the monitored wind turbine's load cases and operational situations. Timewise, the wind turbine was mostly operated in the standard load case of a normal power production under the rated wind speed, most damage occurred in operational times over the rated wind speed and the most relative damage occurred during turbine emergency shut downs.

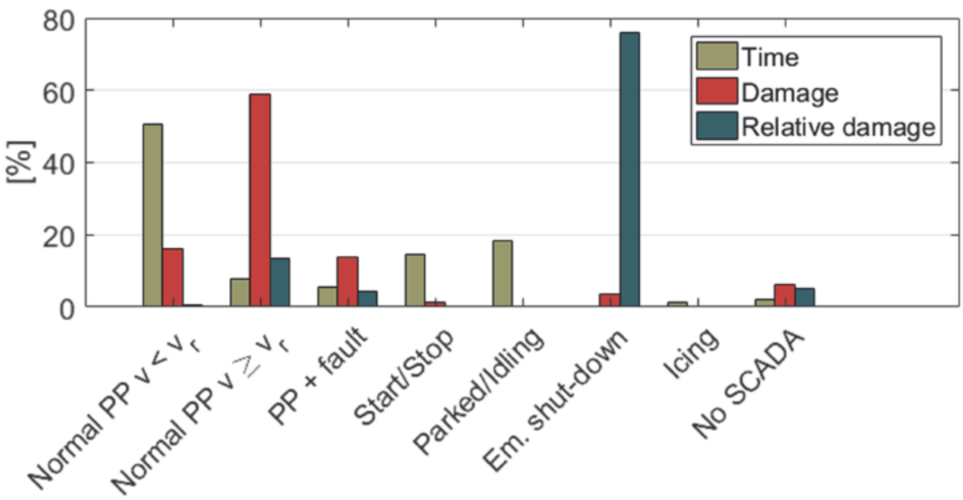


Figure 2-14: Percentage distribution of operational time, damage and relative damage over operations situations in a two year monitoring period (Loraux 2017)

Figure 2-15 accordingly shows the annual damage distribution. It is clearly stated that the annual damage distribution follows the annual wind speed distributions as introduced in chapter 2.1, with peaks and denser air inflow in the winter months and decreased damage accumulation in the summer months. It thus becomes evident that major maintenance and service measures must take place in the summer months.

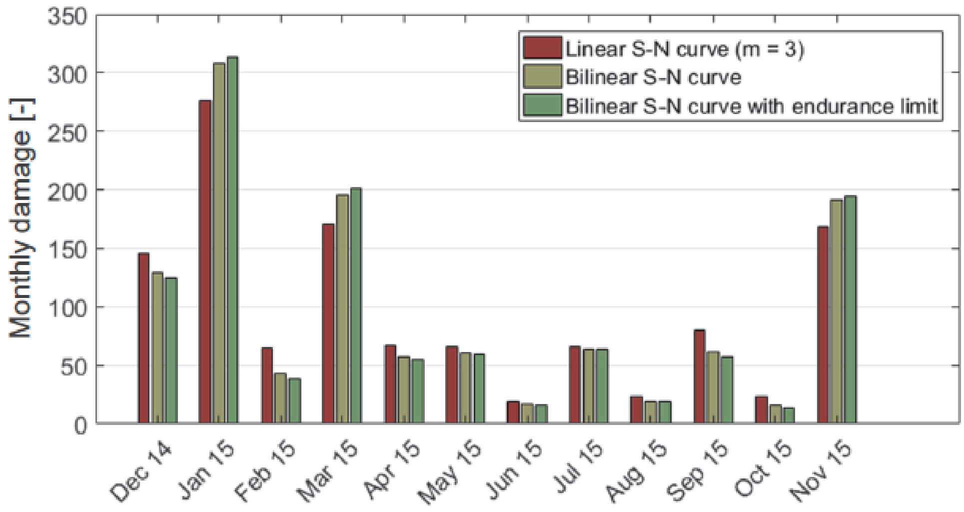


Figure 2-15: Annual damage distribution of a wind turbine system (Loraux 2017)

2.4.3 SERVICE LIFE EXTENSION REGULATIONS FOR WIND TURBINES

In Germany, several authorities on national level are engaged in the process of generating guidelines for certifying service life extensions for wind turbines. First and foremost, the specialists of DNV GL started working on the first service life extension standard for wind turbines in 2006. The first version of the standard was published in January 2009 (Germanischer Lloyd Industrial Services GmbH 2009) and reviewed in 2016 (DNV GL AS 2016c). The standard is valid for wind turbines on- and offshore. The DIBt guideline for the supporting structure system of an onshore wind turbine references on the DNV GL standard for service life extension concerning the structural parts. Furthermore, the German wind industry association – Bundesverband WindEnergie e.V. (BWE) – published consulting papers and established a national working group especially for wind turbine operators on that specific topic (Bundesverband WindEnergie e.V. 2016). The following paragraphs will consolidate the relevant requirements for a service life extension analysis according to DNV GL. The following paragraphs focus on the regulation framework in Germany. Other country specific regulations must be considered in addition. Figure 2-16 describes and defines the different lifetime phases in this framework.

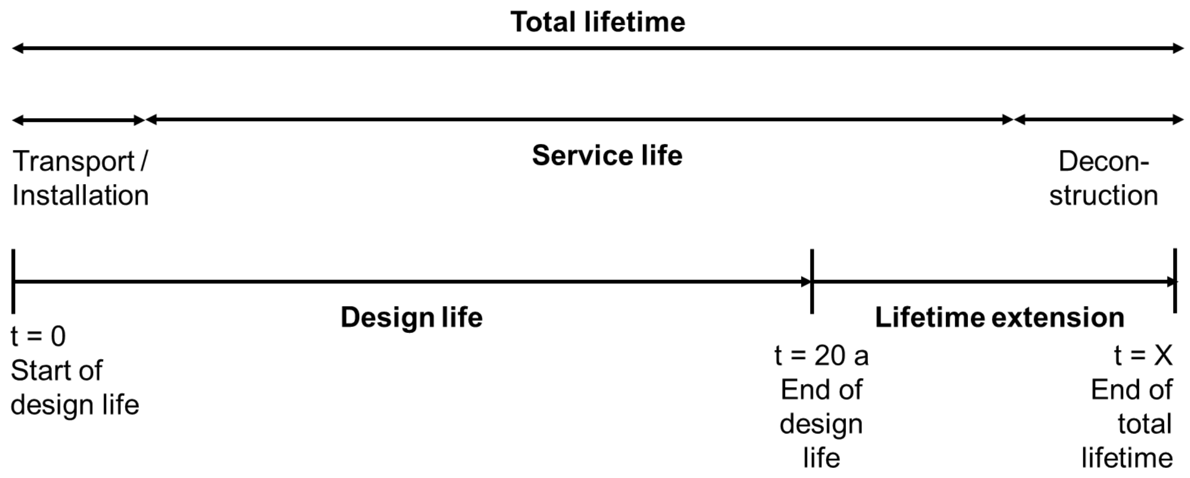


Figure 2-16: Lifetime phases of a wind turbine system

For the design of wind turbines, a design lifetime of 20 years is generally assumed. The extension of service life beyond those 20-years must be justifiable from both a technical and an economic point of view. Issues of structural integrity must be put in front, prior to economic interests. The design life of a wind turbine system can be defined as the time span which was taken as basis for the design calculation including all safety factors. It can be considered that, as a rule, the actual service life of a wind turbine system will be longer than the originally assumed design life. Reasons for this circumstance are multifaceted, to name a few: Excessively high structural safety factors, lower wind supply than expected at most sites, and high unplanned downtimes of the turbine systems due to grid issues or other operational circumstances.

The lifetime extension certification can be performed for wind turbines with a valid or expired type certificate. Thus, the respective wind farm can have a valid or an expired project certificate. Type and project certifications must be seen independent from the lifetime extension certification process. This means that the validity of the respective type or project certificate will not be extended by any lifetime extension certification activity. Furthermore, the applying operator must have a quality management system fulfilling the requirements of ISO 9001. Test and measurement reports handed in for a certification application must be prepared by accredited measurement institutes that meet the requirements of ISO/IEC 17025. In other circumstances DNV GL will witness the test and measurement campaigns. The following list gives an overview of DNV GL publications and references in the light of lifetime extension certification of wind turbines:

- DNVGL-SE-0074 – Type and component certification of wind turbines according to IEC 61400-22
- DNVGL-SE-0073 – Project certification of wind farms according to IEC 61400-22
- DNVGL-SE-0190 – Project certification of wind power plants
- DNVGL-ST-0262 – Lifetime extension of wind turbines
- DNV GL-SE-0263 – Certification of lifetime extension of wind turbines
- GL-IV-1-12 – GL Rules and Guidelines – IV Industrial Services – Part 1 – 12: Guideline for the Continued Operation of Wind Turbines, Edition 2009

- GL-IV-1 – GL Rules and Guidelines – IV Industrial Services – Part 1: Guideline for the Certification of Wind Turbines, Edition 2010
- GL-IV-2 – GL Rules and Guidelines – IV Industrial Services – Part 2: Guideline for the Certification of Offshore Wind Turbines, Edition 2012
- ISO/IEC 17020 – Conformity assessment – Requirements for the operation of various types of bodies performing inspections
- ISO/IEC 17025 – Conformity assessment – Requirements for bodies certifying products, processes and services

Especially in focus are all load transferring components that are relevant for the structural integrity of the wind turbine and the control and protection system. Figure 2-17 describes the minimum inspection scope of a lifetime extension assessment for an onshore wind turbine according to DNV GL. Under consideration should be all listed components and their connections.

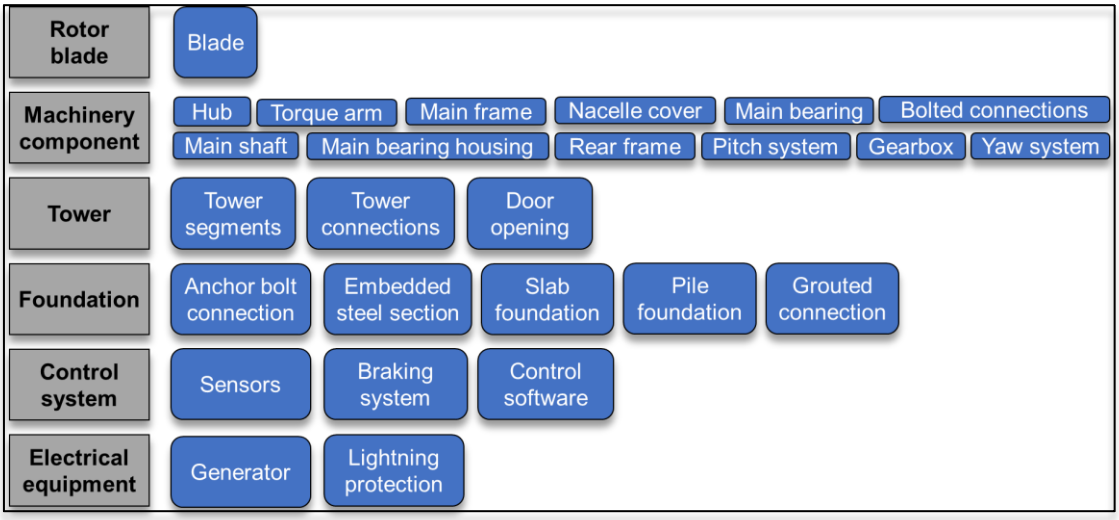


Figure 2-17: Inspection scope of a lifetime extension assessment

The assessment shall always be based on a combination of an analytical part and a practical part. The analytical part incorporates an assessment based on new or additional calculations for the wind turbine, considering the site-specific conditions. The lifetime calculation of the analytical part should be supplemented with relevant field experience of the wind turbine model concerning weak points, known failures, or retrofits. Furthermore, the lifetime extension evaluation should consider current state of the art to ensure a safe operation. Special modifications are not required if the following conditions are fulfilled:

- The turbine is operated under operating and environmental conditions that comply with or are more benign than the original design conditions.
- The turbine does not have any generally known deficiencies being a danger for life and limb or the environment.

It will be assumed, that the wind turbine fulfilled all relevant guidelines and standards at the time of installation.

According to the DNV GL guideline there are four methods of lifetime extension analysis:

1) Lifetime extension inspection
2) Simplified approach
3) Detailed approach
4) Probabilistic approach

Simplified approach

This approach is most suitable for a lifetime extension assessment, when the original design documentation of a turbine is no longer available. The simplified approach is based on a comparison of assumed conditions applied for design and the actual environmental conditions at the installation site of the wind turbine. The calculations should be carried out with a special load simulation tool applying both sets of design and actual environmental conditions. Generally, those simulations are based on a state of the art aero-elastic simulation code, e.g. Flex5 or Bladed. Due to the use of generic models, an evaluation of the respective uncertainty must be considered. Load measurements on the turbine or wind measurements on site can be included additionally. Assessment focus is the fatigue limit state. An assessment of the extreme loads is not required, if the environmental conditions at site are more benign than the original design conditions. Verification of the structural integrity should be provided for all components and their connections – Figure 2-17 - based on a fatigue load comparison. Concerning the environmental conditions at site the wake influence for all turbine locations should be known. In addition, the effective turbulence intensity values for all material relevant slope-parameters of the S/N curves should be stated.

Detailed approach

The detailed approach can be considered as a deterministic approach. The assessment scope aims towards the original design calculation process of a wind turbine. Thus, access to the original design documentation is obligatory. The process of the detailed approach is basically the same as that of the simplified approach: a comparison of the original design conditions with the real environmental conditions, additional consideration of measurements, assessment focus on the fatigue limit state. Moreover, the detailed approach is subdivided in two steps. The first step is performed independently from a specific wind turbine site. The input environmental conditions are defined on type specific level. The second step uses the specific site conditions of the wind turbine under assessment as input parameters. It must be verified that the site-specific conditions are more benign than the type specific conditions. The following parameters are to be investigated in the scope of the detailed approach – main source therefore is the site survey of the respective wind turbine or wind park:

- Environmental conditions
- Soil conditions
- Influence of wind farm configuration
- Other environmental conditions, e.g. temperature, humidity, ice aggregation, etc.

In case a load-bearing component does not fulfill the fatigue verification for an extended service life, the possibility of enabling an extended service life by other suitable measure, e.g. component exchange or condition monitoring, is to be evaluated. This applies for both the simplified and the detailed approach. A turbine-specific inspection program considering scope and intervals must be developed based on the calculation results. Furthermore, the following information must be taken into consideration as part of the assessment:

- Operational history (SCADA data)
- Maintenance history
- Reports from inspections
- Failure reports / reports on extraordinary maintenance activities
- Documentation on exchange of components
- Documentation on changed controller settings
- Field experience with turbine type

Probabilistic approach

The probabilistic approach integrates the use of stochastic methods in the assessment of structural integrity. As an alternative to the use of deterministic values in the simplified and detailed approaches, the probabilistic approach uses appropriate probability distributions to characterize the uncertainty in models and model inputs. The stochastic parameters – such as probability distribution types, expected values, coefficients of variation, or correlation coefficients – in the limit state formulations must be justified, so as not to introduce weakness in the approach. A structural reliability analysis (SRA) in the following course of actions must be carried out:

- Selection of a target reliability level
- Identification of failure modes in the system
- Development of limit state functions (g-functions) for each failure mode based on engineering theory
- Quantification of the deterministic and stochastic variables within the limit state function and their correlations
- Use of appropriate methods (e.g. first order reliability method – FORM) to compute reliability indices or probabilities of failure for the structural components
- Comparison of the computed component reliability with target reliability level for each component
- Analysis of results using sensitivity analysis

The aleatoric and epistemistic uncertainty in mathematic models and input parameters are to be described by probability distributions. The nature of uncertainty being described by the relevant distributions must be clarified. Measurements can be used to update the probability models. The selected statistical technique – Bayesian updating, optimal estimation, etc. – used to characterize the distribution of stochastic parameters for the SRA must be justified. If aero-elastic models or resistance models of the components under consideration are not available, generic load and resistance models can be used. However, the application of a generic model in a structural reliability analysis must include an evaluation of uncertainty of the respective model and the assessment results. Modifications of the controller during the service life must be taken into consideration in the assessment.

In case of insufficient fatigue verification of load bearing components for an extended service life, a suitable measure - e.g. component exchange or condition monitoring – can be evaluated to enable a lifetime extension certification. SRA is already included in Eurocode 0 as an alternative way to demonstrate compliance of an engineering system with safety requirements. Based on the probabilistic approach, risk-based inspection methods may be developed.

Practical part

The practical part is represented by an inspection assessing the wind turbine regarding its suitability for a lifetime extension. The inspection includes all load transferring components, and the control and protection system. Target is to detect fatigue damage of components at an early stage. The inspection intervals must be defined accordingly.

Generally, wind turbines in Germany have to be inspected in intervals of 4 years in the defined design life, or if no annual servicing is applied in intervals of two years.

3 THE IMPORTANCE OF ASSET MANAGEMENT

Figure 3-1: Highest wind turbine in Europe - Enercon E70 at 2.456 m at Griespass, Wallis, Suisse (InfraStructures 2012)

The difficulty lies not in the new ideas, but in escaping from the old ones, which ramify, for those brought up as most of us have been, into every corner of our minds.
John Maynard Keynes (Keynes 1991)

3.1 TECHNOLOGICAL MAINTENANCE HISTORY

The concept of maintenance has undergone notable changes in the last decades. The main reason for the shift of approach was increasing pressure to achieve higher plant availability while containing or reducing costs. However, the increasing understanding of quality and the growing complexity in technical systems were also driving forces. Finally, the development of better maintenance techniques and applied sensor and nondestructive testing systems made asset management in many technical areas an essential discipline in the pursuit of more efficiency and sustainability. Maintenance management can be traced through three generations since the 1930s (Moubray 1995).

The first generation is the period up to World War II on the time scale. The industry was not very highly mechanized, and downtimes did not matter much. Most of the equipment applied in industry was simple, over-designed, and easy to repair. Thus, the early prevention of equipment failure was not a very high priority and systematic maintenance approaches were not needed. A simple repair-based maintenance policy was mostly applied and, in most cases, sufficient. However, servicing and lubrication routines were already in place for more complex systems.

The second generation is placed between the 1950s and mid 1970s on the time scale. In the post-war time, the pressure of demand for goods increased, while industrial man power dropped. This situation drove industry to a higher level of mechanization, more complex machines were designed and operated, and industry and economy began to rely on them more and more. In this atmosphere, the concept of preventive maintenance was born and downtime minimalization came into sharper focus. The conclusion that equipment failures could and should be prevented acted as a catalyzer. This development caused a rise of maintenance cost relative to other operating costs. The first maintenance planning and control systems emerged. Furthermore, engineering theory gained a better understanding of the dependency of failure probability in the service life of components. The development of the well-known “bathtub” curve replaced the concept of linear increasing failure rates over the lifetime of a component in many applications. However, maintenance strategies in the second generation still consisted of equipment overhauls at fixed intervals to a lion’s share. Another side effect of the increased mechanization and more complex machinery was, that the amount of capital invested in fixed assets rose, pushing people to investigate ways to maximize the service life of their assets.

The time frame between the 1970s and 2000s is stated as the **third generation**. Reliability and availability are now key topics in applied methodology and research. Furthermore, the structural integrity of physical assets was given more focus in many branches, especially in offshore and aerospace environments. Also, the concept of Failure Mode and Effect Analysis (FMEA) extended from aerospace applications, to other industrial asset management applications. An important side effect was that more and more component-based views entered the maintenance policies. Upcoming and applicable sensor technology incrementally enabled the usage of condition-based maintenance strategies. Also, the incorporation of asset management tools to maximize the return on investment of physical asset was stressed more extensively.

Maintenance 4.0 constitutes the latest development stage of maintenance as a discipline. Sensor applications in use for condition-based maintenance strategies are used on a broad basis. Also, the benefits of wireless sensor systems are in focus for subsequent sensor installations on existing and operating assets. In environments of data in surplus, data analysis methods are fundamentally important for predictive maintenance strategies, which are employed to avoid unplanned downtimes. Connectivity and system thinking introduce holistic views on modern maintenance optimization problems and find use in modern maintenance management systems. Figure 3-2 displays the main development stages on a generic time scale.

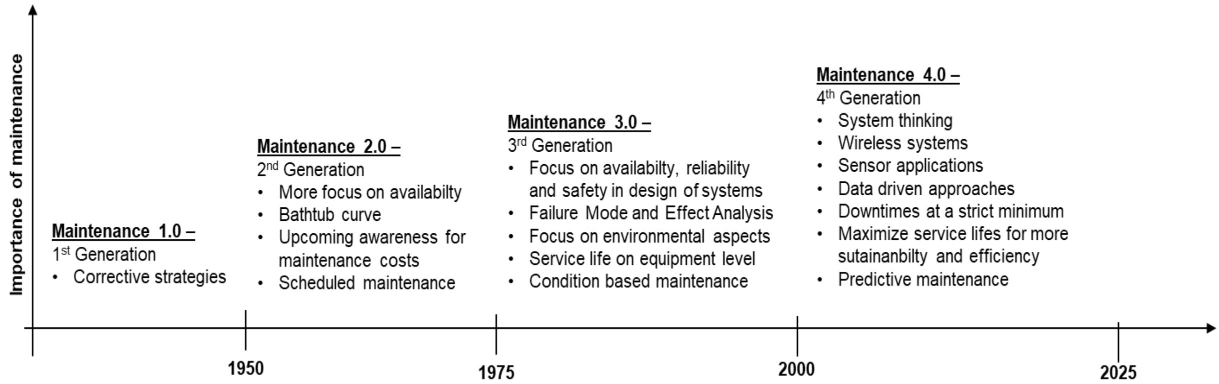


Figure 3-2: Different development stages of maintenance in history

3.2 OPERATIVE MAINTENANCE STRATEGIES

Maintenance is defined as the combination of all technical and administrative actions in the life cycle of a component, with the goal of preservation or restoration of the component's function.

Normative backgrounds like DIN 31051 and DIN 13306 further categorize maintenance in four different tasks: maintenance, inspection, restoration and improvement tasks. **Maintenance tasks** are defined as all tasks to decelerate the degradation of a component's wear reserve. **Inspection tasks** summarize all measures to determine the current wearing condition including cause analysis and the derivation of actions for the ongoing operation of the component. **Restoration** is defined as the physical action to restore the function of a failed component. **Improvement** is understood as the combination of all technical and administrative measures to enhance the reliability, maintainability or security of a component without changing the initial function of the component.

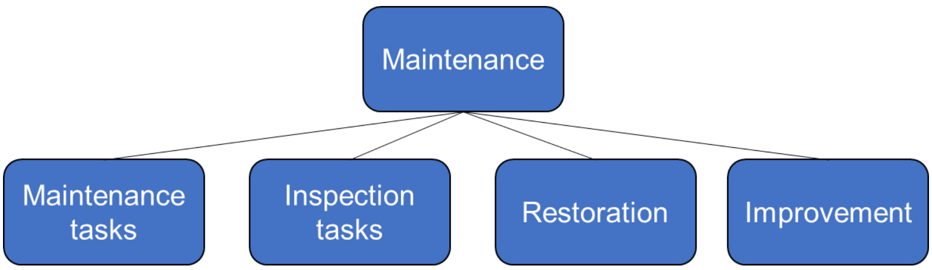


Figure 3-3: Maintenance elements as defined in DIN 31051

The general goal and intention of a maintenance strategy should be to optimize the relation between the availability and criticality of a technical system and the overall cost of ensuring the availability goal.

Availability is defined as the ability of a system or component to be able to fulfill its pre-defined function at a given point in time (DIN EN 13306: 2015-09).

Reliability is defined as the ability of a system or component to be able to fulfill its pre-defined function during operation (DIN EN 13306: 2015-09).

To accomplish this overall goal, there are four general operative maintenance strategy families.

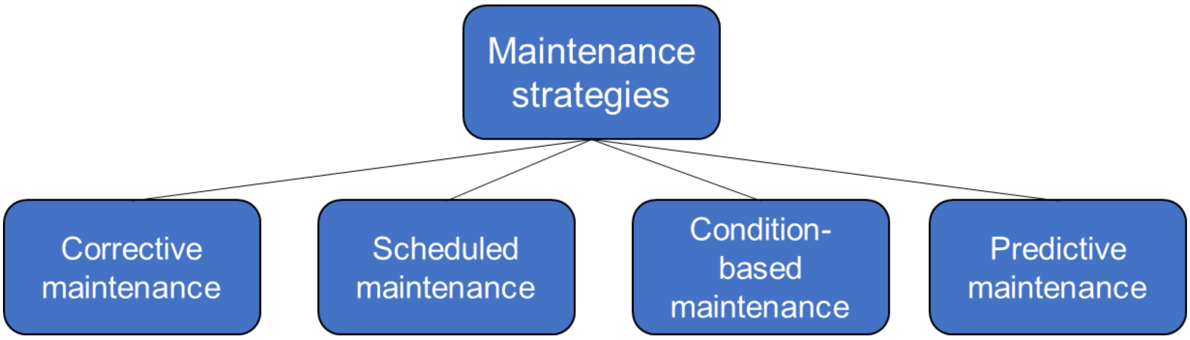


Figure 3-4: Overview of maintenance strategy families

Technical systems in the **corrective maintenance strategy** will be operated until a major failure of a component leads to a shut down. Thus, the full utilization of the component life is guaranteed. However, the strategy can cause unscheduled and long downtimes and induces the risk of a subsequent failure. Synonyms for the corrective maintenance strategy are: break-down-strategy, run-to-failure strategy, or repair strategy.

The **scheduled maintenance strategy** includes a cyclic policy in which components are serviced in fixed periods independent of their condition. The cyclic policy can be clock-based or age-based. Because the maintenance tasks are scheduled, planning possibilities are increased, especially when it comes to an efficient spare part management. Also, a high system availability is guaranteed applying this maintenance strategy. However, the utilization of the component lifetime or wear reserve is not fully guaranteed.

The primary goal applying the **condition-based strategy** is finding the optimum point in time for maintenance actions. Data on the current condition of the component is collected by applying monitoring and inspection techniques on conditionally accessible wearing hot spots. Through early fault detection and following preventive measure, severe damage and damage propagation can be avoided. This results directly in lower repair and downtime cost but generates cost for installing and operating a monitoring and inspection system.

A variety of **predictive** maintenance strategies have been developed. All have in common that reliability data and the probability of failure occurrence is used to optimize maintenance tasks. Applying probabilistic modelling allows the integration of various relevant data sources from field relevant for the deterioration status of the specific components – e.g. information from condition monitoring systems, combined with information from nondestructive testing techniques. Taking into account various data sources and not relying on single hot spot information makes predictive maintenance strategies a powerful set of instruments to focus on optimal use of a component's wear reserves. However, in practice, this is strongly dependent on the information quality and model uncertainties of the applied probabilistic models.

Figure 3-5 depicts the basic maintenance strategies in a generic model graphically in the so called PF-diagram (Potential– failure diagram) (Moubray 1995).

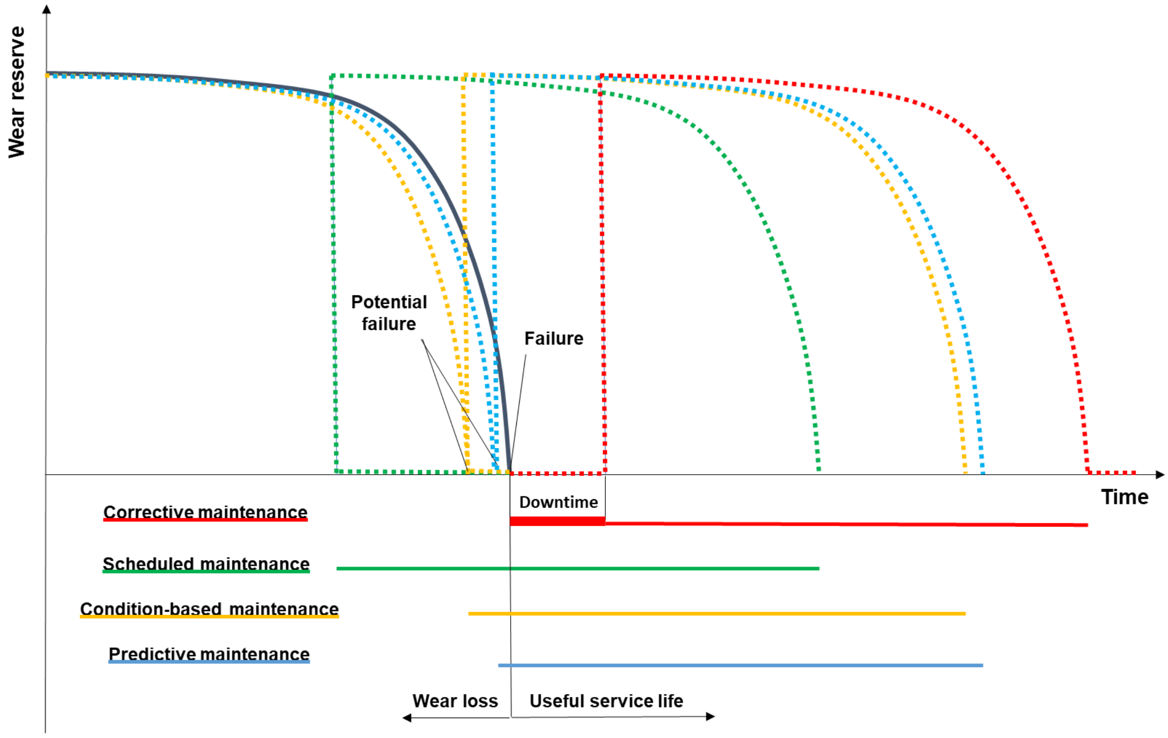


Figure 3-5: Basic maintenance strategies in the PF diagram

3.3 Asset Management in Related Industries

3.3.1 Aerospace Industry and Military Systems

The basic concept of Reliability-centered Maintenance Analysis (RCM) was developed in the 1960s and 1970s in the aerospace industry by Nowlan and Heap (Nicholas and Young 2008). Notable aerospace projects for which RCM was applied are for example the Boeing 747 jumbo jet, the French supersonic passenger jet Concorde, or the American interceptor Mc Donell F4 Phantom. As an advancement of the first basic concept RCM2 was also applicable to other industries in the late 1980s and focused more on environmental hazards of the analyzed systems as RCM in the basic version did. Relevant applications for an RCM2 analysis can be found in the sectors of mining, manufacturing, petrochemicals, utilities, transport, buildings, and military. The decision logic or decision algorithm of an RCM analysis is based on a functional classification of the analyzed system and leads directly to the recommended service strategy on a component level, whereby the economic efficiency and safety issues play a key role. Moubray provides a comprehensive reference of the methodology and its application (Moubray 1995).

To ensure availability, reliability, and safety, airborne rotorcrafts utilize data collection and analysis systems, so-called health and usage monitoring systems (HUMS). After the offshore crash of a commercial Chinook helicopter in 1986, industry experts began to develop HUMS technology and regulation. Besides safety issues, HUMS nowadays are primarily used for maintenance strategy and operational cost and performance optimization, including reduced mission aborts, improved mission reliability, and simplified logistics. An industry overview of HUMS activities is given in Adams (2012). Polanco gives a summary of applied sensor and data analysis techniques in HUMS (Polanco 1999). Practical examples of HUMS deployments can be found in Greaves (2014). A general overview of HUMS methods in aerospace can be found in Willis (2009).

Structural health monitoring in aerospace applications is based on two basic structural failure concepts, the safe-life and the damage-tolerant concept. Safe-life components are planned to be replaced, before cracking occurs. Damage-tolerant components are monitored concerning the concept of crack propagation analysis. Furthermore, in the latter cases it is assumed that damage-tolerant components fail safe.

Based on these concepts, IABG and Airbus developed a structural integrity and lifetime health monitoring system for the TORNADO-Fighter program in Europe. The design of the asset management system was based on a hot-spot approach. Main design criteria for the asset management system were location of critical areas, type of structural damage, stress level, and spectrum and specifications of the data acquisition system. The high homogeneity enabled the engineers to apply a fleet management concept, in which not all structural components of every fighter had to be monitored, but instead could be extrapolated from monitored fleet leaders (Boller 2009; Pettersson et al. 2010).

The developments of Integrated Logistic Support (ILS) methodologies began in the 1960s in the military and defense industry. The primary goal of ILS is to integrate all relevant support and maintenance activities for a military system in one framework during the whole product life cycle. Economic and efficiency aspects play an important role in development and deployment of the ILS methodology. The basic pillars of ILS can be found in Jones (2006).

3.3.2 OFFSHORE AND MARITIME INDUSTRY

The Petroleum Safety Authority Norway established the Offshore and Onshore Reliability Data (OREDA) project in 1981. The original objective was the collection of reliability data of equipment in the petroleum industry. Nowadays OREDA covers a wide range of reliability data from equipment used in oil and gas exploration and production systems. The primary goal of the database project is to contribute to enhanced safety and cost-effectiveness in operation and maintenance activities in oil and gas facilities. Systematic data collection and analysis of O&M data is seen as the fundamental task, establishing a high reliability, availability, and safety standard among the industry. The database includes offshore, subsea, topside, exploration, prediction, and downstream equipment. In some cases, weak or failure prone points in a sub-system are also recorded. Furthermore, the data analysis concept characterizes failure modes and is concerned with the determination of root causes.

Currently, a group of several petroleum and natural gas companies cooperate in the OREDA project team. The database provides a unique data source on failure rates, failure modes, repair times, and corresponding statistical parameters.

3.3.3 NUCLEAR INDUSTRY

Emerging from the conventional power supply sector we know the concept of RAMS, which integrates the most relevant operational demands for power supply systems, which are:

- **Reliabilty;** as the system's ability to perform its function, often given as a design or operational reliability value
- **Availabilty;** as the ability of a system to be kept in a functioning state
- **Maintainabilty;** as the ease with which the system can be maintained or repaired
- **Safety**; as the requirement to not affect the environment in a negative way

The nuclear industry developed asset and life management systems for critical components and deterioration processes in their plants. A strict certification policy demands proof of structural integrity at the end of a certification period. Especially thermal conditions and fluids inside the systems enhance the fatigue processes. The French OEM AREVA designed a special methodology to approach fatigue issues in this framework. Lifetime extension projects of nuclear components were conducted in the USA, Sweden, and Switzerland. Especially the long service-life periods of up to 60 years for new plants demand a holistic long-term asset and lifetime management system. Furthermore, the changing load cycles in the transforming energy systems, due to more and more decentralized privileged renewable energy systems, require on-line monitoring of the fatigue design reserves (Rudolph et al. 2012)

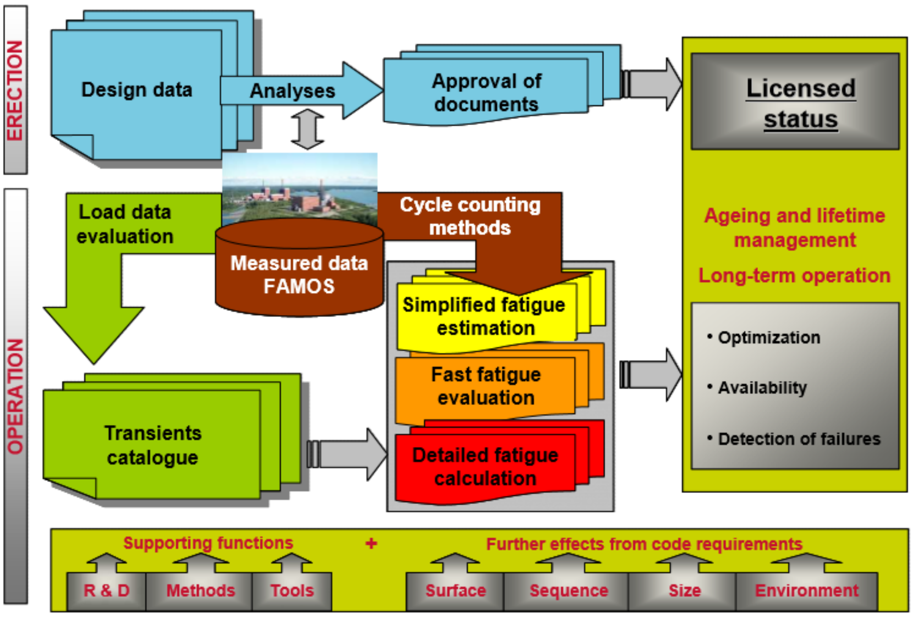


Figure 3-6: FAMOS methodology (Rudolph et al. 2012)

The core methodology of the Fatigue Monitoring Systems (FAMOS) – as depicted in Figure 3-6 - was originally developed at SIEMENS in the 1970s for monitoring of German nuclear plants. The monitoring methodology is based on a three-stage system, using cumulative usage factors (CUFs). If the cumulative values exceed a specific threshold, the component enters the next level of detailed fatigue analysis. The initial simplified fatigue analysis considers a hot-spot analysis. The fatigue process stages are estimated based on operational plant data. The second fast fatigue evaluation considers a re-calculation of the fatigue evaluation using data from sensors mounted on the relevant component. The third detailed fatigue estimation level applied high-resolution models to validate the actual fatigue state with the acquired sensor data.

Moreover, AREVA developed a holistic database concept, in which sensor data, operational data, and inspection data are holistically integrated, stored, and managed - COMSY. Vattenfall also developed such nuclear databases as information system for collecting, processing, and analyzing failure statistics and reliability parameters for the whole nuclear power industry.

3.3.4 ASSET MANAGEMENT IN THE WIND ENERGY INDUSTRY

The wind energy industry has not yet achieved an integrative asset management framework. One of the main deficits are the missing systematics in the overall asset management goal on a strategic and operative level, and in finding the optimal maintenance and spare part strategy, the maintenance process itself, the maintenance documentation, and data analysis – to name a few. The current data availability and data quality are low. There is no consistent information structure. A uniform incident classification system throughout the wind industry is not state of the art, therefore operational and maintenance incidents cannot be described one-to-one. Thus, the description of failure modes, root causes, and subsequent failures is biased, and logical conclusion and historical analysis for a sustainable system knowledge to prevent severe failures is only possible to a limited extent. Lifetime documentation of wind turbines is incomplete and fragmentary, not digitalized and sometimes non-existent. If some data is available, technical incident data and the resulting operation and maintenance cost data are acquired and stored in different systems with no logical connection. Consequently, it is extremely difficult and extensive to carry out comprehensive maintenance analysis studies. Considering maintenance software and computerized maintenance management systems (CMMS), proprietary and isolated software solutions inhibit integrative and holistic views on complex maintenance problems. General integrative standards are missing or in stage of development and not ready for broad industry application. Furthermore, the communication between all persons involved in the operation and maintenance activities of wind turbines needs to be improved.

A major future topic will be lifetime-extension programs of wind turbines reaching the end of their original design life, carrying considerable structural wear reserves which need to be used for a more sustainable and economical operation of wind turbine systems.

This assessments go along with the outcomes of the IEA Wind Task 33 Reliability Data: Standardizing Data Collection for Wind Turbine Reliability and Operation & Maintenance Analyses which was published in 2017 (Hahn et al. 2017).

Figure 3-7 defines the different life cycle phases of a wind turbine system in general. By far, the operations and maintenance phase in the life cycle can be the most cost intensive phase.

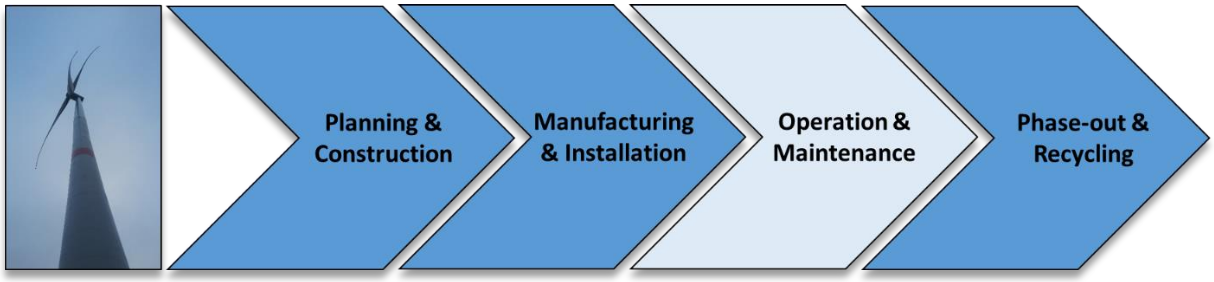


Figure 3-7: Life cycle phases of a wind turbine system

Generally, a majority (approximately 75 %) of the failures with which operating and maintaining personnel must deal occurs in the first two life cycle phases, design, planning, construction, manufacturing, and system installation. Moreover, approximately 80 % of the overall system failures only occur in the operation and maintenance phase. In addition to further pretests and more effort in quality management in wind turbine manufacturing sites, a necessity is to integrate maintenance and operational needs, specifications, and experiences into the planning and design phase of the turbine. Furthermore, designing systems for maintainability, is a necessary step to guarantee optimal serviceability and a more sustainable service life. E.g. one important aspect is a good accessibility to install monitoring and inspection systems at physical wearing hot spots, which will be of interest in the operational phase. The operational and maintenance phase of wind turbines is characterized by the pursuit of avoiding unplanned downtimes as far as economically proportionate, and therefore applying the correct and optimal maintenance strategy according to criticality measures on component level to ensure a high system reliability. Toward the end of the original design life of 20 years, lifetime extension activities and certifications must be evaluated from an entrepreneurial point of view on macro and micro economical scales. Figure 3-8 describes the basic life-cycle model for wind turbine systems and the related primary asset management goals. The analysis in this framework mainly focuses on asset management actions which can be taken after the wind turbine systems are installed; however, early actions in the construction phase – e.g. precise quality control and process adjustments – can also have intensive positive results on the wind turbine system reliability.

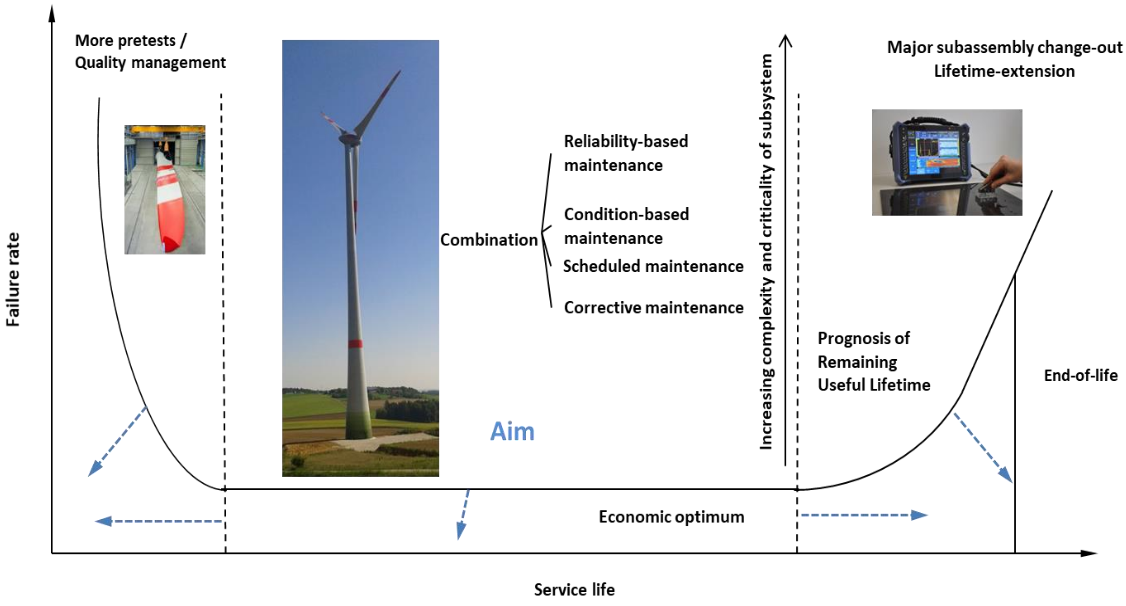


Figure 3-8: Life cycle model of a holistic asset management strategy in the bathtub curve

3.4 THE PROJECT MISTRALWIND

The MISTRALWIND project (acronym for Monitoring and Inspection of Structures at Large Wind Turbines; partners: Technical University Munich, Siemens AG, Industrieanlagen-Betriebsgesellschaft mbH) focused its research activities on developing innovative and reliable methods and sensor systems for analyzing the remaining useful lifetime (RUL) capacities of a wind turbine structure. The consortium consisted of the Technical University of Munich with the Chairs of Nondestructive Testing, Structural Analysis, and the Centre for Building Materials, Siemens Corporate Technology, and IABG mbH as consortium leader. Max Bögl AG acted as an associated partner within the consortium providing a real wind turbine supporting structure. The project started in August 2015 and was completed in July 2018. Funding was provided by the German Federal Ministry for Economic Affairs and Energy (Project 0325795E). Figure 3-9 depicts the overall project structure of the MISTRALWIND research project.

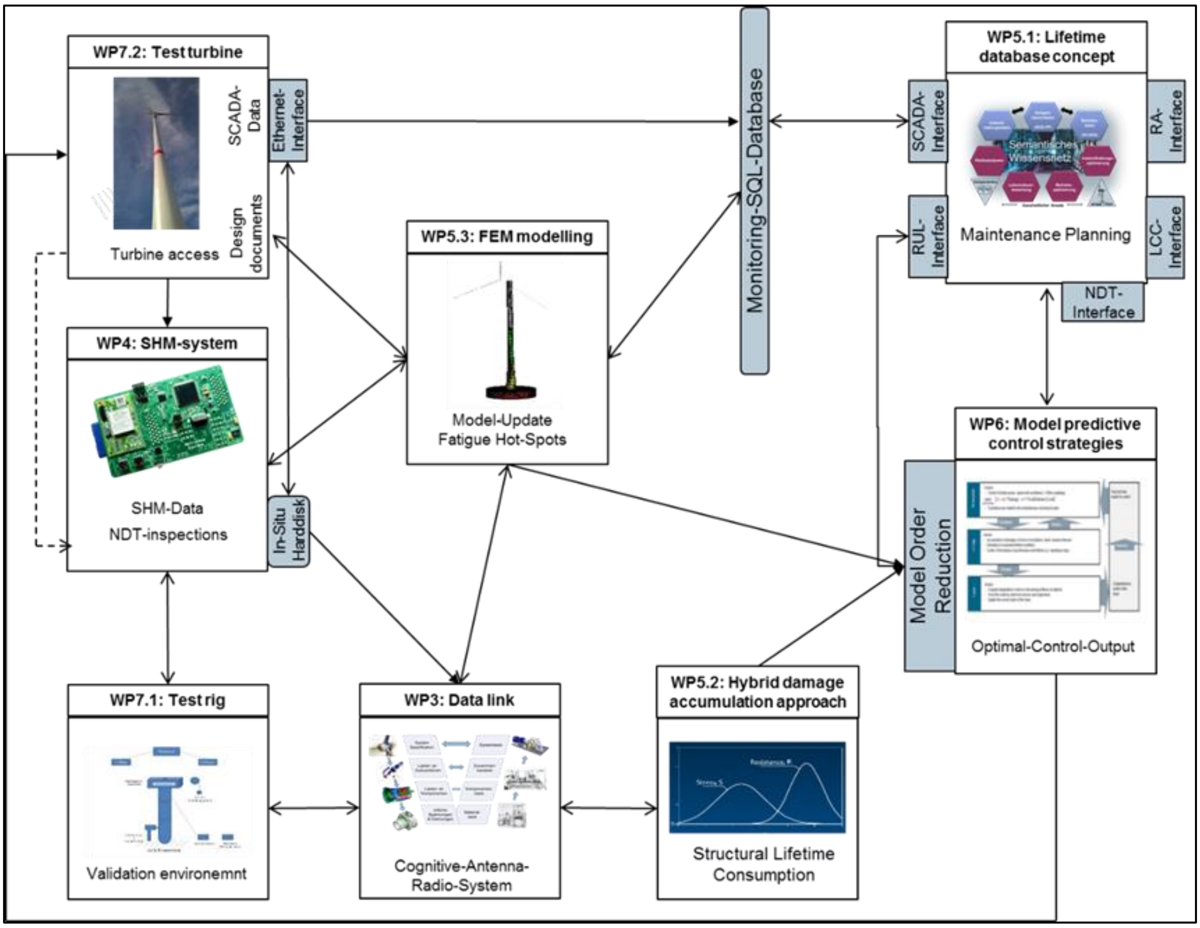


Figure 3-9: Project structure and interfaces in the MISTRALWIND project (Geiss et al. 2017)

To allocate hidden lifetime resources of wind turbine structures, it was necessary to permanently monitor the stress applied to the wind turbine tower. In work package 4 – as displayed in Figure 3-10 - a wired modular monitoring system was installed by Botz, Raith and Wondra on a 3 MW wind turbine with a concrete-steel hybrid tower design in Northern Bavaria, Germany (Botz et al. 2016; Botz et al. 2017a; Raith et al. 2016; Wondra et al. 2016).

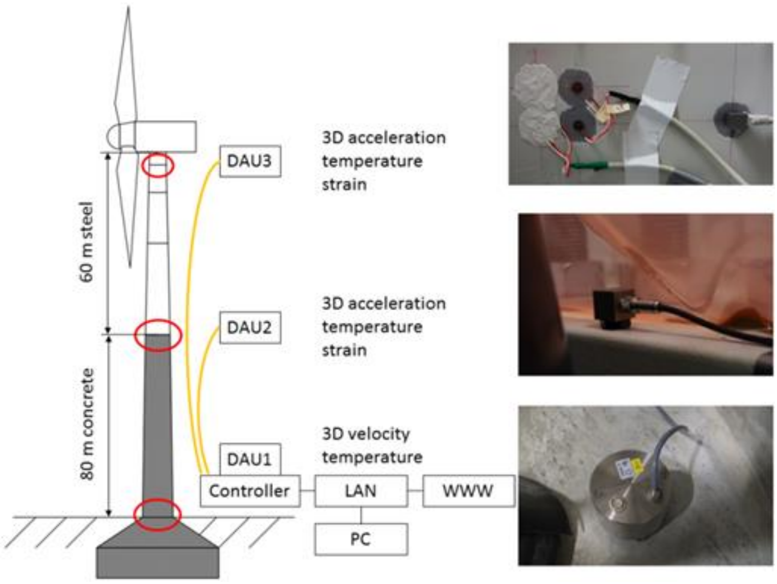


Figure 3-10: Setup of monitoring system on test wind turbine (Geiss et al. 2017)

Operational Modal Analysis was conducted by the Chair of Nondestructive Testing using vibration data to update a FE-model of the tower according to its modal parameters (Botz et al. 2017b). The covariance driven stochastic subspace identification (SSI-COV) method returned the most dominant modal properties of the test wind turbine's tower during idle state, as listed in Table 3-1.

Table 3-1: frequency and damping of wind turbine in idle state (Geiss et al. 2017)

Eigenmode	**Frequency in Hz**	**Damping in %**
1st bending ∥ rotor plane	0.270	0.66
1st bending ⊥ rotor plane	0.272	0.39
1st torsion	0.810	0.36
2nd bending ∥ rotor plane	1.040	0.49
2nd bending ∥ rotor plane	1.070	0.33
2nd bending ⊥ rotor plane	1.173	0.30

Based on the developed SHM concept it was the goal to analyze the remaining useful service life capacities of the structural parts of the wind turbine and to design integrated asset management and service strategies to optimize the technical availability and service life consumption under optimal costs. For extension of the SHM system, wireless sensor nodes were installed on the test turbine in summer 2016 (Raith et al. 2016; Wondra et al. 2016). To verify the accuracy of the FFT conversion on the sensor chip, the wireless sensors were installed on a vibration test rig at the IABG facilities in February 2017 and raw acceleration values were recorded at heights of 1.9 m and 5 m. The test station applied various vibration curves with frequencies of up to 200 Hz onto the test station's pole structure and the mounted wireless sensors. In parallel, the pole structure was equipped with wire-based acceleration sensors of high resolution.

The goal of the FEM application in work package 5 of the project was to determine the relevant fatigue regions in an efficient way and support the estimation of the remaining useful life of the analyzed wind turbine tower during its operational time and support the measurement actions by a priori determination of the possible fatigue hot spots. The fatigue analysis of the complete structure by the Chair of Structural Analysis and the Chair of Materials Science and Testing required a rigorously detailed modeling which in return resulted in a computationally costly way of simulating the system's response; this was prohibitive for transient operational analysis over long time-spans. For that reason, a multi-fidelity modeling approach was pursued. Initial modeling adopted a shell structure that consistently reduced the continuum to its mid-plane by making use of finite elements that rely on the Reissner – Mindlin theory rather than a corresponding beam theory. This enabled the computation of localized stresses around geometrical features, such as openings, as well as the consideration of feature variations along the tower, such as cross section, wall thickness etc. As aforementioned, a second, computationally more efficient, model that details the hot spots while sparing computational expense from the uncritical zones was used for further analysis and "on the fly" analysis of the remaining life time of the wind turbine support structure. A part of the constructed CAD-Model is presented in Figure 3-11.

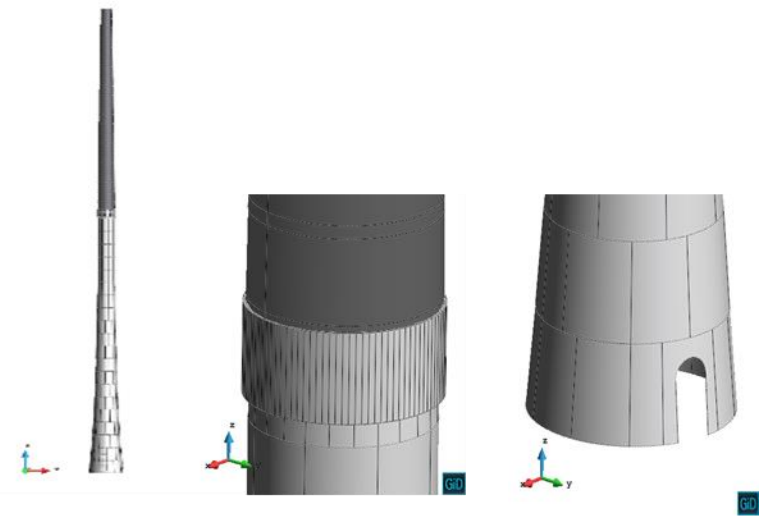


Figure 3-11: Hybrid tower, steel-concrete junction and tower entrance door in detail (Botz et al. 2017a)

In light of the performed eigenfrequency analysis, it was assumed that the transient response, i.e. displacements of the structure, could be approximated by the extracted dominant eigenmodes. Thus, the stress states of the tower in time domain were computed as a linear combination of the stress states of each eigenmode. This indicator was used for hot spot analysis of the support structure. Furthermore, it was used for the further detailing and simplification of the necessary regions. The Von-Mises stress states of the first four bending modes at the concrete part of the tower are presented in Figure 3-12. It was observed that due to the tower design, the highest stress exposures did not only occur at the root level or close to the openings, e.g. door, holes, but also in varying locations along the tower shaft.

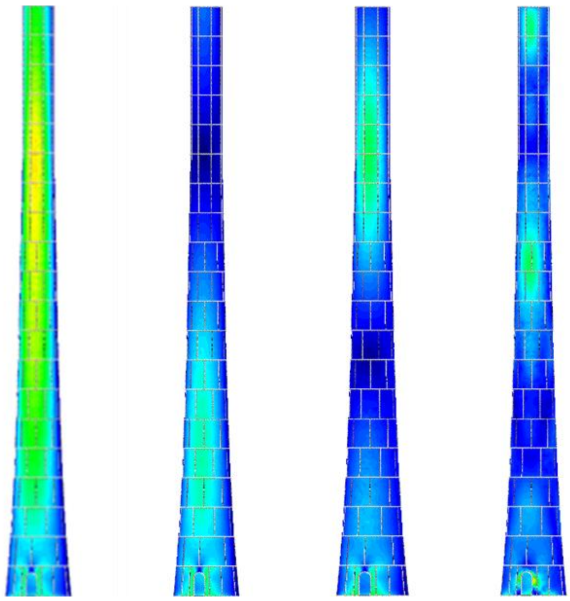


Figure 3-12: Von – Mises stress states of the first four bending modes at the concrete part of the tower. The color plots are scaled to their individual min-max ranges to emphasize the hot spots of each eigenmode (Geiss et al. 2017)

Simulations running in parallel to operation required real time capable models. A real time capable model is the base for model predictive control (MPC). Model order reduction (MOR) directly reduces the 3D CAD models. After space discretization, linear partial differential equations are represented by large linear systems. Model order reduction techniques reduce the corresponding matrices. For commercial tools, this technique is integrated directly in the CAE-tools. The FEM model of the tower was implemented on a finite element solver, therefore the reduction capability also required redevelopment. The reduced model was compared to the comprehensive FEM model. The number of degrees of freedom was reduced from about one million to 10. The input force acted on the upper node of the tower, which represents the connection to the nacelle. The resulting displacements were taken at the same node.

The primary goal of the wind turbine control was to regulate (typically maximize) the energy generation while guaranteeing that the dynamics of the turbine remain in an acceptable regime. The typical control variables are the pitch angle of the blades, which were changed individually or collectively, and the electric generator torque which was regulated by power electronics. Although there are different strategies for controlling turbines, the standard approaches are reactive, i.e. they react to the change in the wind by adjusting the rotor speed and the power set-point. A simplified linear tower model used in MPC is obtained by model-order-reduction of the FEM model. For standard steel towers, an acceptable approximation of the tower dynamics for control purposes is of the order two. In other words, the tower dynamics are, in the simplest form, presented as a movement of a concentrated mass on top of the tower. For hybrid, i.e. concrete and steel, towers, the resulting model is of a higher dimension. The tower is, in the fore-aft direction, excited by the thrust force which is also modeled as a non-linear function of the rotor speed, pitch angle, and the equivalent wind speed. MPC is an optimal control problem over a short-time interval repeated for every controller sample. Not only is this optimization complex due to the non-linearity of the turbine dynamics, but also because of the intrinsic constraints on the control variables and on the system states. The involved constraints on the system states are those of the rotor speed, of the maximum power, and the power rate of change. Simultaneously, both control variables are constrained in their magnitude and in their rate of change.

The designed cost function by Siemens Corporate Technology is of the integral type and contains several possible contacting terms. The first term is the integral of the generated power over the optimization time interval, i.e. the generated electric energy. Since the tower fatigue is of interest, it is implicit to have a cost function also containing a term dealing with (i.e. penalizing) it. Unfortunately, the aging of the turbine is a process of much slower time constant than that of the rotor speed dynamics. Hence, it is not possible to optimize fatigue directly over the interval in the range of seconds where the MPC is active; it is done indirectly by penalizing the energy of the oscillation of the tower in the frequency range around its eigenfrequency (Münz et al. 2015; Rodenhausen and Obradovic 2017; Hartmann et al. 2018; Weeger et al. 2016).

The relationship between the short-term control of MPC and the long-term goals of affecting the tower fatigue is depicted in Figure 3-13.

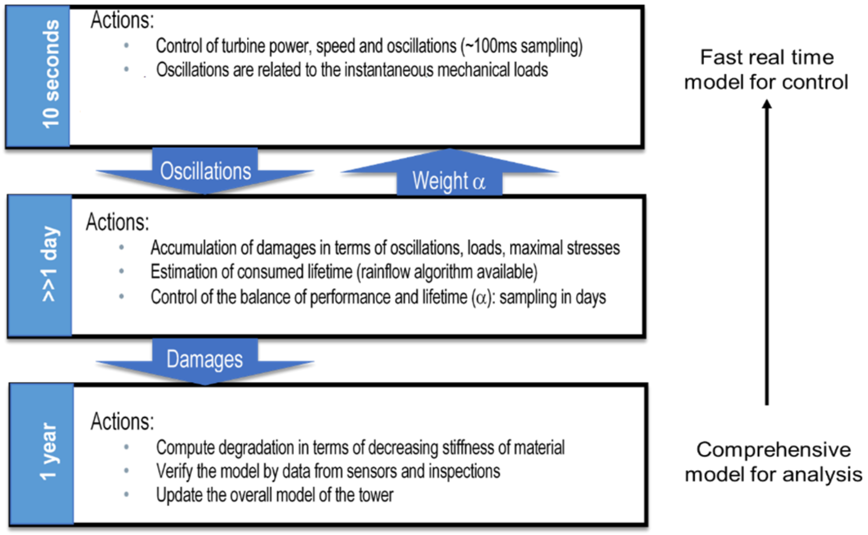


Figure 3-13: MPC time levels (Geiss et al. 2017)

In this way, the long-term observation of the tower aging (fatigue accumulation) can be used to change the weighting of the terms in the cost function over time. The higher penalization of the tower oscillations should make the control actions less aggressive and slow the aging over time.

In engineering theory there are models to describe the specific fatigue mechanisms which cause wearing of a structural element, e.g. linear damage accumulation (Haibach 2006). However, these models inherit implied model uncertainties. Those model uncertainties can be reduced by in-field inspection data. NDT methods under this aspect are an effective risk mitigation measure for existing structures. Risk-based inspection planning (RBI) essentially has the goal of using probabilistic methods for the (cost-) optimal allocation of deterioration control. The underlying probabilistic concept can be fully qualitative, fully quantitative, or an individual mix of both. However, all probabilistic methods used in an RBI-framework have the concept of risk prioritization in common, which means that the inspections are planned due to the risk of failure of an individual component. Thus, the probabilistic approach strikes a balance and enables quantification of system state without the obligatory need to have deterministic input from complex sensor systems or detailed design models which are often not available due to OEM restrictions.

3.5 INTERIM CONCLUSIONS

To answer research question **RQ 2**, the following section summarizes the findings:

What is the status quo in wind turbine asset management and which requirements can be considered for a holistic asset management concept?

The status quo in wind turbine asset management is describable as a transitional state. Energy generation from wind developed from a rather ideologic energy conversion technique to an integral component of the energy system of the future. To guarantee marketable energy prices, integral asset management concepts will play a key role. The wind energy industry has not yet achieved an integrative asset management framework. One of the main deficits are the missing systematics in the overall asset management goal on a strategic and operative level, and in finding the optimal maintenance and spare part strategy. The current data availability and data quality are low. There is no consistent information structure. A uniform incident classification system throughout the wind industry is not state of the art, therefore operational and maintenance incidents cannot be described one-to-one. The description of failure modes, root causes, and subsequent failures is biased, and logical conclusion and historical analysis for a sustainable system knowledge to prevent severe failures is only possible to a limited extent. Lifetime documentation of wind turbines is incomplete and fragmentary, not digitalized and sometimes non-existent. If some data is available, technical incident data and the resulting operation and maintenance cost data are acquired and stored in different systems with no logical connection. Considering maintenance software and computerized maintenance management systems (CMMS), proprietary and isolated software solutions inhibit integrative and holistic views on complex maintenance problems. General integrative standards are missing or in stage of development and not ready for broad industry application. A major future topic will be lifetime-extension programs of wind turbines reaching the end of their original design life, carrying considerable structural wear reserves which need to be used for a more sustainable and economical operation of wind turbine systems.

Considering the system distribution of the wind turbine investment cost, gearbox, rotor blades and the tower and supporting structure are the most capital-intensive subsystems. To optimize the cost-yield ratio of wind energy from an operator’s view, increasing the annual power output by reducing unplanned maintenance downtimes, lengthening the service life of the wind turbine while retaining a reasonable reliability level, and reducing the overall maintenance and repair cost are the main levers. A holistic asset management concept should mainly provide methods and tools to ensure an optimal service lifetime – also beyond the originally designed 20 years of design life, while guaranteeing a high availability of the system at optimal cost. Excessively high structural safety factors, lower wind supply than expected at most sites, and high unplanned downtimes of the turbine systems due to grid issues or other operational circumstances, provide a fruitful basis in the field. Especially in focus are all load transferring components that are relevant for the structural integrity of the wind turbine and the control and protection system. The asset assessments in an integrated asset management approach shall always be based on a combination of an analytical part and a practical part. Currently over 3,000 wind turbine systems already have exceeded their original designed service life of 20 years. A majority of the overall capacity of German wind energy installations is older than ten years – approx. 56 % - and already in its second half of service life. Similar age structures of the overall wind turbine capacity can be found all over Europe, especially in Spain, the UK and Denmark. For most of these turbines, the original design documentation will not be available to the operators. Therefore, simplified approaches using data available to the operators – such as SCADA data – must play a key role in an integrated asset management framework. The application of generic and deterministic engineering models need consideration of the respective uncertainty. Load measurements with structural health and condition monitoring sensor systems as well as nondestructive inspection techniques should also be included to reduce model uncertainties. A turbine-specific inspection program considering scope and intervals must be developed based on the calculation results. Furthermore, the following information must be taken into consideration as part of the assessment:

- Operational history
- Maintenance history
- Reports from inspections
- Failure reports / reports on extraordinary maintenance activities
- Documentation on exchange of components
- Documentation on changed controller settings
- Field experience with turbine type
- Based on the probabilistic approach, risk-based inspection methods may be developed.

All information available to the operators must be integrated in an operational data base management system, logically linking and storing all different data streams.

4 INTEGRATED ASSET MANAGEMENT SYSTEM

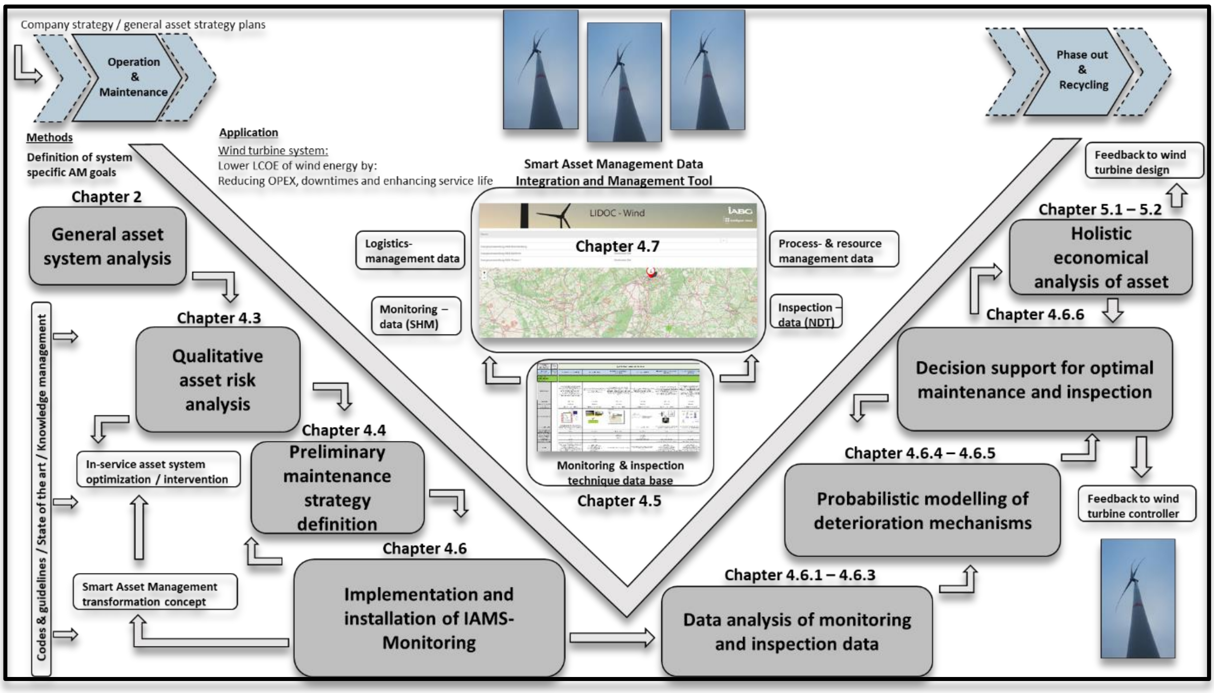


Figure 4-1: Integrated Asset Management System for Wind Turbines (IAMS-Wind)

Will man Schweres bewältigen, muss man es leicht angehen.

Berthold Brecht

4.1 DESIGN OF THE INTEGRATED ASSET MANAGEMENT SYSTEM CONCEPT

To answer research question **RQ 6**, the following sections display the findings:

How should a holistic and integrated asset management concept for wind turbines be designed?

The Institute of Asset Management (IAM) defines Asset Management as the following: “Systematic and coordinated activities and practices through which an organization optimally manages its physical assets, and their associated performance, risks and expenditure over their lifecycle for the purpose of achieving its organizational strategic plan” (The Institute of Asset Management 2017).

There are two approaches of maintenance optimization: qualitative and quantitative. Qualitative maintenance optimization is often biased with subjective opinion and experience. Quantitative maintenance optimization employs mathematical models in which the cost and benefit of maintenance are quantified and an optimum balance between both is obtained.

The concept for an integrated asset management system, subject in this thesis, is developed under the objective of designing a holistic and integrated asset management system for wind turbines from the management process level to the specific sensor application – and back. The basic design is displayed in Figure 4-1. Similarly, the IAMS-Wind concept provides the logical framework for the main chapters of the thesis.

The approach designed in this thesis is mainly driven by the development of asset management methods. Wind turbine systems, their importance in the macro-economic perspective of a renewable energy system and their complexity on a technical level provide a fruitful framework.

A core element of a future integrative asset management system for wind turbines must be a holistic operational data base management system, which integrates all data streams relevant for wind turbine operation and management activities of each life cycle phase. Figure 4-2 displays the defined life cycle phases of a wind turbine system according to new regulations (DIN SPEC 91303:2015-03). From an asset management view point, the operation and maintenance time frame – Life Cycle Phase (LCP) 6 to 8 – is the most important, wherein asset management activities can directly influence the plant performance. However, all other life cycle phases must also be contemplated for their asset management requirements. For instance, the basic plant configuration and quality framework is set at the beginning of the whole plant life cycle and therefore defines specific boundary conditions in which asset management optimization must take place. Most of the failures which lead to unplanned maintenance downtime and directly influence the technological and economic performance of wind turbine systems are rooted in the design, construction, and erection phases. Finally, the decommissioning and recycling phases of wind turbine systems have to be considered as last and sustainable life cycle phase of wind turbine systems, in which criteria and strategies for life time enhancement activities, de-investment strategies, and recycling possibilities have to be considered. As integrated economical approach – implying all life cycle phases – holistic cost-associated evaluation methodologies must be established. Economical asset analysis for most turbine operators is paramount on a micro-economical scale, however, macro-economic scales must also be considered to empower a higher level of sustainability. Naturally, economic performance is strongly dependent on the technical condition in which the turbine system and its components are, however, an integrative asset management system must always consider the optimization behavior of technical maintenance and enhancement activities according to the economical dimension. A certain level of risk of unplanned downtimes and unreliable systems needs to be considered from an operator's view point, however, current risk analysis methodologies in the wind energy sector make it difficult to quantify operational risks, thus risk and cost optimal maintenance strategies are not yet deployed, but strongly needed in a future fully competitive renewable energy market. To seek and find such optimal asset management strategies, operators depend on adequate field information. Concerning this matter, current sensor technology for monitoring and inspection techniques should be analyzed according to their suitability in specific monitoring or inspection tasks, deployed, and integrated in a future holistic asset management framework of wind turbines. Data acquired with sensor technology must be processed with specific algorithms, integrating all those views, and enable optimization in such a framework.

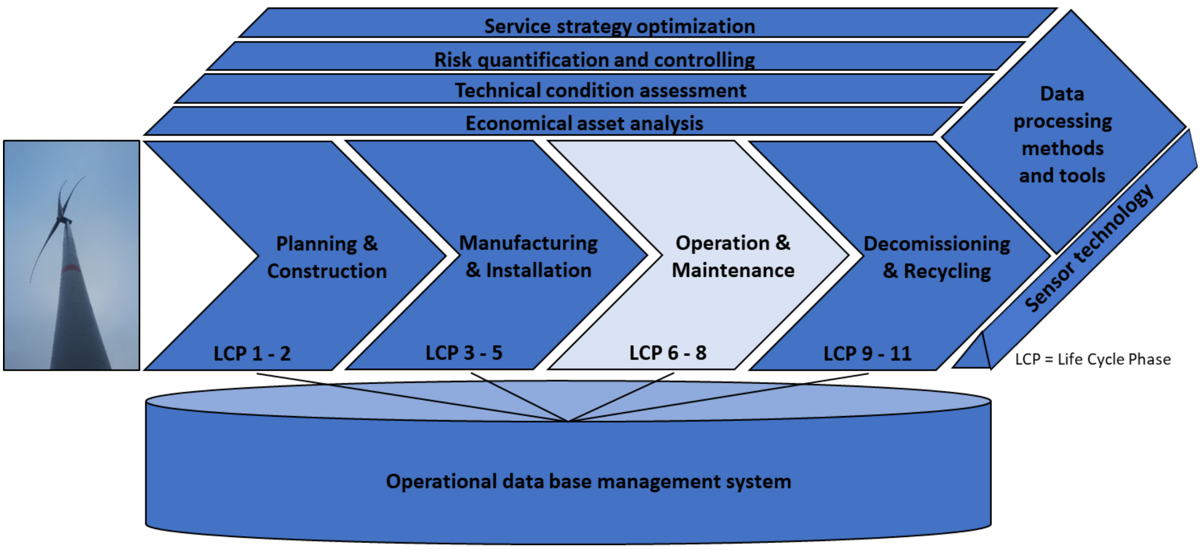


Figure 4-2: Concept of holistic life cycle asset management of wind turbines

Besides, an integrated asset management system for wind turbines must also consider the new developments in general asset management as defined in the new asset management standards and proof conformity.

The ISO 55000 series of standards represents a general management standard and is linked with other major management standards like ISO 14001 for environmental management systems, ISO 9001 for quality management systems, or ISO 31000 for risk management. Therefore, AM systems according to ISO 55000 are defined as integrated management systems. Compared to other management standards in this category, the ISO 55000 set is relatively new. The specifications were developed based on PAS 55 - Optimal management for physical assets (PAS55:2008), which was originally a British standard developed from the British Standards Institution (BSI). The main difference in comparison is that the ISO 55000 specifications do not solemnly focus on physical assets. The ISO 55000 series is expected to become the global standard of asset management of technical and non-technical systems.

The ISO 55000 standard family consists of three parts:

- **ISO 55000: Overview, principles, and terminology**
- **ISO 55001: Management systems – Requirements**
- **ISO 55002: Asset management – Management systems – Guidelines for the application**

The set describes the tasks and the general role of asset management within an organization. Specific requirements and recommendations for design, implementation and updating of an asset management system are given. Those specifications range from a strategic level to an operational level. The second part ISO 55001 defines the requirements for design, implementation and improvement of an AM system. Furthermore, the second part defines the certification requirements for organizations. ISO 55001 and ISO 55002 provide detailed specifications with respect to the different branches, types of assets and activities.

All areas and branches of an organization should be involved into an AM system, however the initiation and target definition for the AM system has to be done on management level.

Considering the type of organization, the target group for ISO 55000 systems is the following:

- **Capital-intensive industrial organizations** like chemical industry, production industry, aerospace industry, automotive industry, etc.
- **Energy and water industry organizations** like energy providers, grid operators, renewable energy providers, water and environmental service providers, etc.
- **Infrastructural organizations** like airport operators, railway operators, highway operators, infrastructural operators in the public sector, etc.

Within this scope an asset management system can be defined as the coordinating and controlling system of all activities in planning and target attainment of the pre-defined asset management goals. As described in chapter 1.2 wind turbine systems are one of the most important assets in the renewable energy system and therefore should be considered under the ISO 55000 framework. As an ISO management standard, ISO 55000 primarily defines specifications on an organizational level. Definitions and specifications on activity level in the different application branches are not provided in details. However, the general framework for the design of an asset management system is well defined and specified.

ISO 55001 introduces top-level information requirements and performance evaluation requirements for an asset management system on the management standard level.

- **General information requirements** (7.1) for an asset management system, information on:
    - Risks
    - Roles and responsibilities
    - Asset management processes
    - Exchange of information between different roles
    - Impact of quality, availability and management of information on organizational decision making

- Furthermore **detailed information requirements** (7.5) should consider:
  - Attribute requirements of identified information
  - Quality requirements of identified information
  - How and when information is to be collected, analyzed and evaluated
  - Processes to maintain the information should be specified
  - Traceability of financial and technical data must be considered

The conception of performance evaluation within the ISO 55001 framework defines requirements for monitoring, measurement, analysis and evaluation of technical and financial data in an asset management system.

- **Performance evaluation requirements** (9) should determine:
  - What needs to be monitored and measured
  - Methods for monitoring, measurement, analysis and evaluation
  - When monitoring should be performed
  - When monitoring data should be analyzed
  - Reports on the asset performance and the effectiveness on the AM system
- Based on the performance evaluation the standard defines specific **management reviews** on
  - Non-conformities and corrective actions
  - Monitoring and management results
  - Change of risk profiles

Besides, the standards also specify potential information sources for an asset management system. The following compilation represents an excerpt of the most relevant data sources:

- **Information sources of asset management**
  - data management;
  - condition monitoring;
  - risk management;
  - ..
  - environmental management;
  - systems and software engineering;
  - life cycle costing;
  - dependability (availability, reliability, maintainability, maintenance support);
  - configuration management;
  - …
  - sustainable development;
  - inspection;
  - nondestructive testing;
  - pressure equipment;
  - financial management;
  - value management;
  - shock and vibration;
  - acoustics;
  - qualification and assessment of personnel;
  - project management;
  - ..
  - equipment management;
  - commissioning process;
  - energy management.

Figure 4-3 displays the general asset management process as defined in ISO 55000.

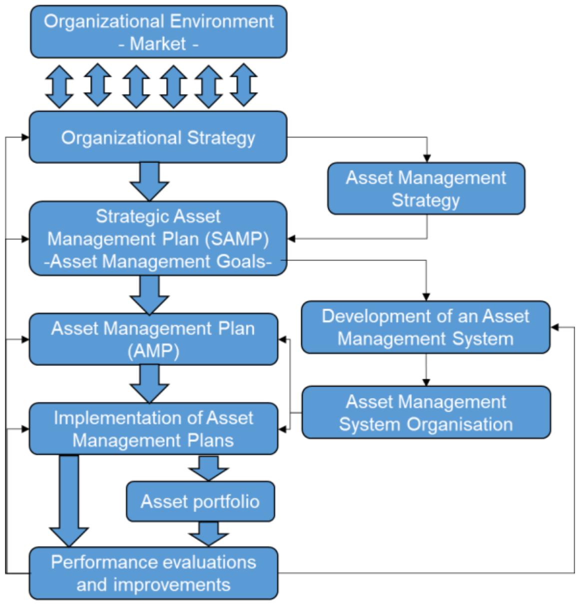


Figure 4-3: Asset management process in ISO 55000

According to the ISO 55000 understanding of asset management, the asset management strategy of an organization should be defined in coordination with the general strategic goals of an organization. Thus, an organization's asset management strategy will bear a decisive importance looking at general business strategies and goals in a global market in every maintenance-intensive industry, especially in the energy sector. Derived strategic asset management goals should be summarized in a strategic asset management plan (SAMP) on a higher level. Based on those strategic asset management guidelines, plant-specific asset management plans (AMP) will be implemented to translate those strategic views into technological dimensions, holistically taking into account maintenance needs and requirements of assets under consideration. Simultaneously, also organizational parameters and future requirements on asset management organizations, to run new asset management strategies, have to be considered, which should lead to a holistic asset management organization. Last, to realize a sustainable process organization in the sense of continuous improvement, performance evaluations of the asset management systems have to be carried out to adjust and optimize such asset management systems constantly.

The following integrated asset management concept for wind turbines (IAMS-Wind) will implement those requirements, definitions and needs for a wind turbine system.

4.2 INTEGRATED ASSET MANAGEMENT SYSTEM FOR WIND TURBINES

To the author's knowledge, so far there exists no holistic and integrated asset management system for wind turbines. However, several research projects in the field of wind energy engineering and structural health monitoring developed technologically specified approaches to contribute to the optimized asset conditions of wind turbines. Kamieth et al. (2013) developed a structural health monitoring approach based on short-term measurements and subsequent extrapolation algorithms to predict the remaining useful lifetime of the main sub-systems of a wind turbine. For the structural health monitoring part, the approach deploys acceleration sensors which are correlated with strain measurements. Additionally, relevant maintenance and SCADA-data of the wind turbine system are logged. Classified under the respective load cases along IEC 61400-13 and under the provision of a sufficient data base, the correlated fatigue counting data – *Rainflow* counting – is extrapolated considering a service life basis of twenty years. As most critical point of the approach, Kamieth states the reliability and accuracy of the deployed sensor systems. Rolfes et al. (2008, 2013) also developed several approaches focused on damage detection of structural parts of wind turbines and based on a combination of strain and acceleration measurements. Last but not least Devriendt et al. (2013) developed approaches based on operational modal analysis to detect damages and predict the remaining service life reserve of wind turbine supporting structures.

However, none of the state-of-the art approaches to condition and health monitoring of wind turbines considers a holistic approach, which integrates all relevant requirements to holistically optimize the cost of energy from wind turbines from an asset management point of view.

The following passages will introduce a holistic and integrated asset management concept for wind turbines (IAMS-Wind).

Figure 4-1 displays the holistic and integrated asset management concept for wind turbines which was developed by the author in the framework of this dissertation. The following chapters and paragraphs will lead the reader through the concept step by step. Furthermore, a complete overview of the concept is also given in Annex B.

First and foremost, asset management strategies should be defined considering the general company strategy and the role of the assets as fulfilling entities within this framework. As stated in chapter 4.1 a breakdown of the asset strategy planning on a strategic level (SAMP), as well as on an operational plant level (AMP) is obligatory. This deductive approach should result in the definition of plant-specific asset management plans, inheriting all cost-relevant data and strategically relevant data for the specific asset. Strategically relevant for wind turbine systems considering their overall goal in the energy system is foremost to sustainably lower the cost of energy from wind as stated in chapter 1.2. This overall goal can be subdivided into three underlying goals – as depicted in Figure 4-4 – considering the leverage which can be influenced from an asset management view point.

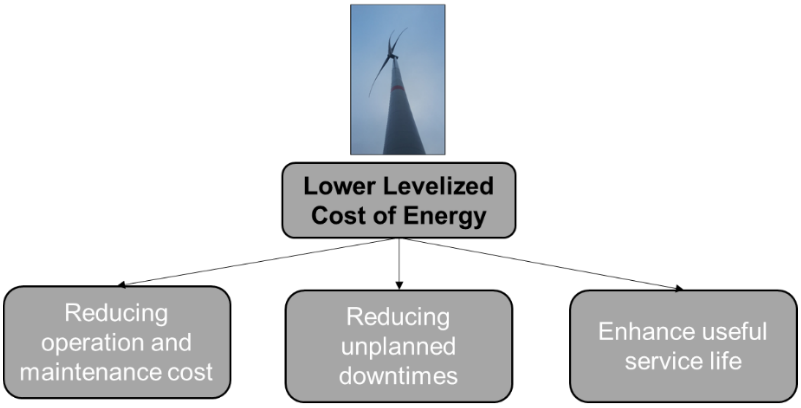


Figure 4-4: Strategic asset management goals of wind turbine systems

The next step in the IAMS-Wind concept is a qualitative risk analysis of the wind turbine system, which identifies, categorizes and mitigates risks on a qualitative level. Finally, this step will lead to a preliminary asset management strategy definition on component level.

4.3 RISK ANALYSIS OF A WIND TURBINE SYSTEM

To answer research question **RQ 3**, the following sections display the findings:

Which sub-systems of a wind turbine system induce the most risk potential from an asset management view point?

4.3.1 STATUS-QUO IN WIND TURBINE RELIABILITY RESEARCH

Research projects in the past gained empirical data to assess the system reliability of wind turbines. Several databases have been established over the last three decades. Table 4-1 summarizes the most relevant wind turbine reliability surveys in the past 30 years. All databases and surveys listed below differ considering monitoring period, number, size and type of turbines, definition of subassemblies and failures, level of detail and in the overall structure.

Table 4-1: Summary of wind turbine reliability surveys

Institution	**Survey name**	**Territory / Country**	**Scope**	**Data structure**	**Time frame**	**Source**
Kema	*NN*	The Nether-lands	- 10 GW of operating wind turbines	- Operational expenditures - Availability data - Component replacement rates	2000 – 2009	(Lantz 2013)
Garrad Hassan	*NN*	Europe	- 1,000 WTs	- Reliability data - Concluded in ReliaWind	2000 – 2009	(Lantz 2013)
Landwirtschafts-kammer Schleswig-Holstein	*Windenergie Praxis-ergebnisse*	Schleswig Holstein / Germany	- 2,500 WTs	Annual reports - Output data - Operational expenditures - Failure data	1993 – 2006	(Eggersglüß 1991-2009)
Fraunhofer Institute for Wind Energy and Energy System Technology	*WMEP / 250 MW Wind Programm*	Germany	- 1,500 WTs - 64,000 maintenance and repair reports	- Failure data - Repair and maintenance measures - Energy production data - O&M cost data	1989 – 2006	(Echavarria et al. 2008)
Fraunhofer Institute for Wind Energy and Energy System Technology	*Offshore-WMEP I & II*	- Germany	- 300 WTs ~ 1,000 failure events	- Component data - Operational data - Failure data	2009 – 2016	(Pfaffel et al. 2016) (Faulstich et al. 2012)
IZP Dresden mbH	*Erhöhung der Verfügbarkeit von WEA I & II*	- Germany	- WMEP data	- Component data - Operational data - Maintenance data - O&M cost data	2008 – 2015	(Jung 2016); (Jung 2012)
WindStats	*WindStats Newsletter*	Denmark and Germany	- 2,000 WTs in Denmark - 2,750 WTs in Germany	Quarterly reports - Output data - Failure data - Component-wise	1999 – 2001	(WindStats 1999 - 2001)
Electric Power Research Institute	*NN*	California / USA	- 290 WTs	- Output data - Failure data	1986 – 1987	(DOWEC 2002) (Electrical Power Research Institute 2016)
VTT Technical Research Center of Finland	*Wind Energy Statistics in Finland*	Finland	- 162 WTs	- Output data - Failure data - Failure causes - Failure actions - Component-wise	1992 – present	(Pettersson et al. 2010)
Elforsk	*Vindstat Database*	Sweden	- 723 WTs before 2005 - 80 WTs after 2005	- Output data - Failure data - Failure specified in type and cause - Incomplete reporting	1988 - present	(ELFORSK 2016)
Reliawind study	*Reliawind database*	Europe	- 350 WTs	- Output data - SCADA data - Fault logs - Service reports	2008 – 2011 450 months	(Gayo 2011); (Wilkinson and Hendriks 2010)

Sandia National Laboratories	*CREW-Database*	USA	- 900 WTs	- Output data - SCADA data - Benchmark of US wind turbine fleet - Reliability data - Component-wise	2011 – present	(Sandia National Laboratories 2016); (Peters and Ogilvie 2009)
National Renewable Energy Laboratory	*NREL Gearbox Failure Database*	USA	- 289 gearbox failure incidents	- Gearbox failure modes - Failure root causes - Detailed failure data	2009 – present	(National Renewable Energy Laboratory 2016)

Furthermore, some publications compared the different surveys among each other and consistently came to the conclusion that substantiated conclusions are difficult due to statistical fuzziness and low statistical population in the single data bases (DOWEC 2002; Lantz 2013; Sheng 2011)

Also, for conventional powerplants there are several empirical reliability databases. One of the most comprehensive ones is the so called KISSY-Kraftwerksstatistik (VGB Powertech e.V. 2016).

Criteria for choosing an adequate evaluation should be statistical population, permanence, granularity and consistency.

The WMEP database (German for: Wissenschaftliches Mess- und Evaluierungsprogramm) represents the most comprehensive empirical basis for the long-term reliability behavior of onshore wind turbine systems in Germany until 2017. The obtained data is gathered component-wise and depicts annual failure rates, mean time between failures, downtimes, and other basic data for system specific reliability evaluations with a minimum time range of ten years. Reliability is understood and defined in the magnitude and range of annual failure rates. In the WMEP-database the parameter failure rate is simply defined as the reciprocal value of the Mean Time Between Failure (MTBF) of the relevant components. Furthermore, the different wind turbine models and scales can be categorized in four generations of onshore wind turbines:

- First generation: < 500 kW
- Second generations: 500 kW < 1,000 kW
- Third generation: 1,000 kW < 3,000 kW
- Fourth generation: > 3,000 kW

First and foremost, mechanical wear out has been the failure case for most shut downs in field. Storms, lightning, icing, and grid outages mostly affected the electrical components. In those failure cases the root cause was mainly found in the control system. Three quarters of the control system failures were rooted in the board or processor of the wind turbine control systems. Electrical components are also extinguished to wear out processes, which need to be analyzed in more details for a better technical understanding of failure cases connected with electrical components.

Considering the technical development of wind turbine systems Jung (2012) shows that with the increasing technical complexity of pitch regulated turbines, the system reliability of wind turbines decreases. All failure rates of all components except the mechanical brake increase for pitch-regulated wind turbines. The development of variable speed concepts leads to a decreasing reliability in electrical components, mainly for generator, converter, cabling, sensors, and control. A general trend towards higher annual failure rates over the technological development can be detected for the electric system, electronic control system, sensors, the yaw system, rotor blades, generators, and the drive train system.

Concerning the severity of the reported and monitored failures, the primary measure is the downtime of the turbine due to a specific failure case. It can be assumed that failure cases causing a long turbine down time are also severe in repair cost. Again, the root cause for the severest failures was mechanical wear out. 75 % of all failures were responsible for only 5 % of the turbine downtime. The remaining 25 % are responsible for 95 % of the turbine downtime. However, it must be stated that in many cases, a failure root cause remains unknown and is not detectable due to considerable difficulties of system knowledge (see also chapter 4.7). Figure 4-5 shows the main result of the WMEP system reliability analysis.

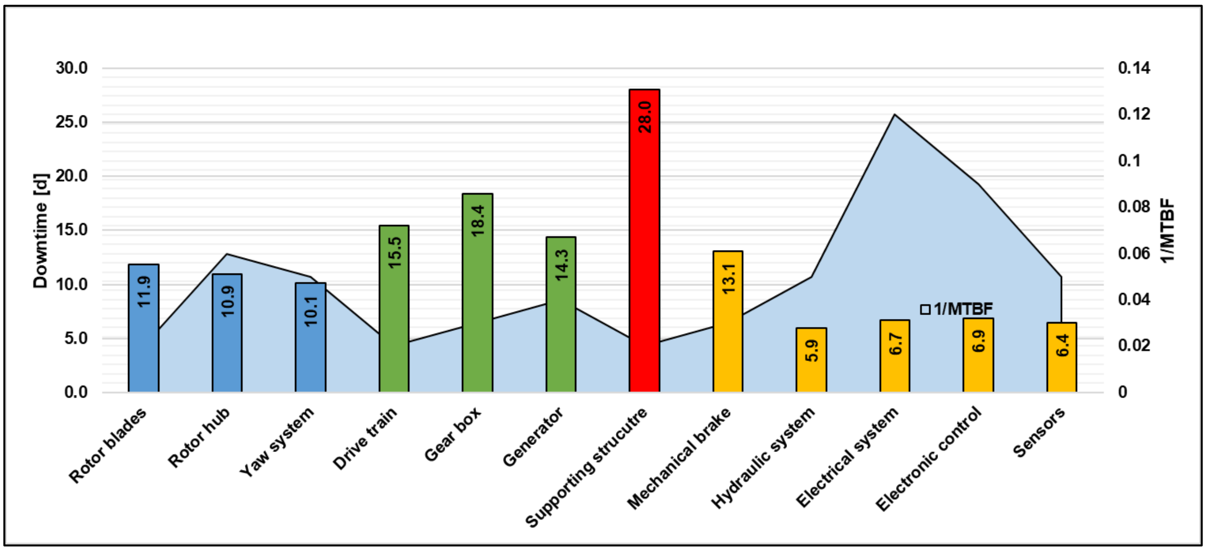


Figure 4-5: WMEP empirical reliability survey results: annual failure rate vs. downtime – adapted from (Faulstich et al. 2011)

For a better understanding of the general reliability behavior of wind turbine systems it is expedient to differentiate the turbine system into its main subassemblies and analyze the differentiated system criticality.

4.3.2 FAILURE-MODE-AND-EFFECT-ANALYSIS OF A WIND TURBINE SYSTEM

The Failure-Mode-and-Effect-Analysis (FMEA) represents a systematic design analysis tool for potential failure modes of technical systems or processes. Traditionally it is used in the design phase of a product or before systematic changes are introduced. The basics of the technique were developed and used in the US space flight projects in the 1960s. The method was first proposed by the NASA in 1963 (Coutinho 1964). While the technique was already established in aerospace applications. Henry Ford implemented the approach the first time for automotive applications in 1977 (Ford Motor Company 2001). Nowadays the methodology is well renowned in several industries, from automotive, to process and nuclear industry (Guimaraes et al. 2011; Kumar et al. 2011; Liu and Tsai 2012; Teng and Ho 1996). The traditional FMEA has been proven to be one of the most effective early prevention tools in design, process or service of systems, which prevents failures and errors in operation. Following the original methodology, the investigations take place in expert teams with one team leader coordinating the project. The general goal of the analysis is to identify actions to prevent failures based on expert knowledge. The different failure modes are categorized in different qualitative risk levels. FMEAs take place on component level and are therefore defined as a bottom-up-approach. The typical procedure of a FMEA is depictured in Figure 4-6. After a detailed analysis of the relevant functions in the system, specific failure modes of the functions in the systems are identified by an expert panel. For each failure mode the effects are to be determined and matched on the severity ranking scale. The next step is concerned with the root cause analysis of each failure mode and leads to the qualitative probability determination of the failure occurrence. In the third and last step, the experts are concerned with the analysis of the current control strategy. Based on the currently applied control techniques – e.g. monitoring and inspection techniques – a rating scale for the detectability of the specific failure mode and root cause combinations is defined.

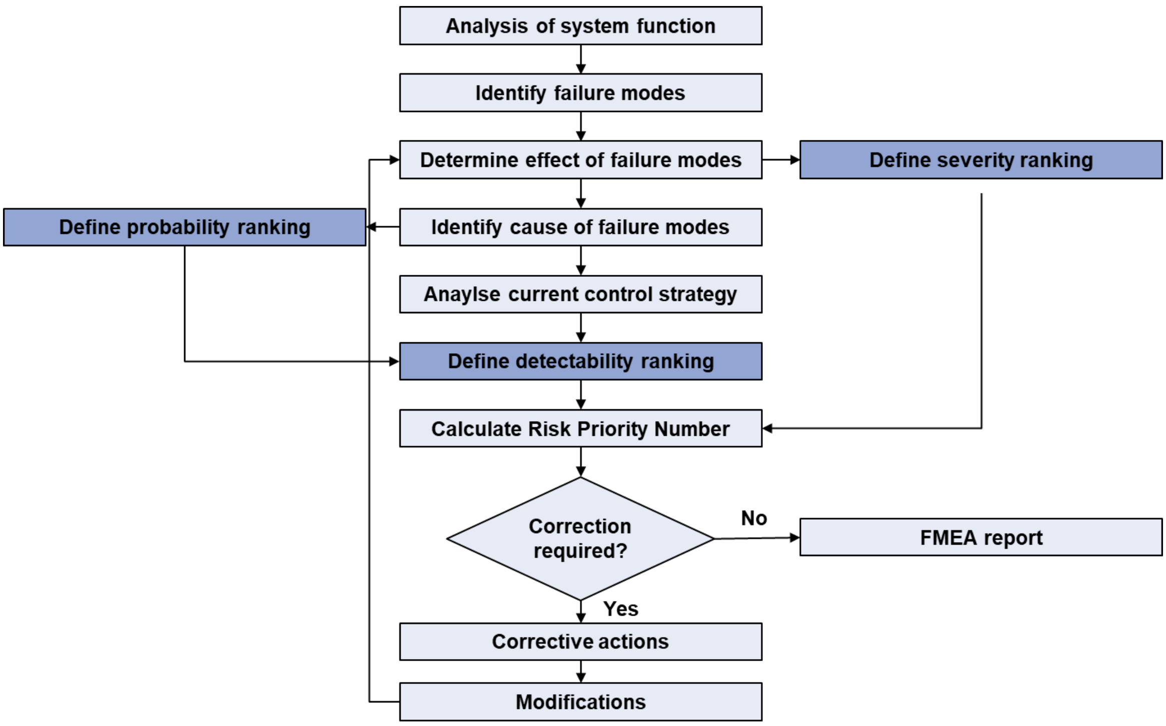


Figure 4-6: Classic procedure of a FMEA analysis – adapted from (Gray and Pfeufer 2017)

Table 4-2 depicts an individually developed FMEA ranking scale for wind turbines. The probability ranking scale is based on the occurrence probability scale from the Automotive Industry Action Group (Gray and Pfeufer 2017). The consequence ranking scale is mainly oriented on safety and production risks.

Table 4-2: FMEA rating scale

Consequence ranking scale - S		Probability ranking scale - P			Detection ranking scale - D	
None: No effect	1	**Very high:** Failure is almost inevitable	≥ 1 in 2	10	**Almost certain:** Monitoring will almost certainly detect a potential failure	1
Very minor: No safety issues; low possibility of production loss	2		1 in 3	9	**Very high:** Very high chance that monitoring will detect a potential failure	2
Minor: No safety issues; high possibility of production loss	3	**High:** Repeated failure	1 in 8	8	**High:** High chance that monitoring will detect a potential failure	3
Very low: No safety issues; very low loss of production (< 2 h)	4		1 in 20	7	**Moderately high:** Moderately high chance that design control will detect a potential failure	4
Low: No safety issues; low loss of production (< 12h)	5	**Moderate:** Occasional failures	1 in 80	6	**Moderate:** Moderate chance that design control will detect a potential failure	5
Moderate: Very low safety issues; moderate loss of production (< 24 h)	6		1 in 400	5	**Low:** Low chance that design control will detect a potential failure	6
High: Low safety issues; high loss of production (> 24h)	7		1 in 2000	4	**Very low:** Very low chance that design control will detect a potential failure	7
Very high: Moderate safety issues; high loss of production (>72 h)	8	**Low:** Relatively few failure	1 in 15000	3	**Remote:** Remote chance that design control will detect a potential failure	8
Hazardous: Severe safety issues; total loss of turbine	9		1 in 150000	2	**Very remote:** Very remote chance that design control will detect a potential failure	9
Very hazardous: Very severe safety issues; total loss of turbine	10	**Remote:** Failure unlikely	1 in 1500000	1	**Impossible:** Monitoring cannot detect a potential failure / No monitoring installed	10

Eventually, the Risk Priority Number (RPN) is calculated according to the following scheme:

$$RPN = S \; x \; P \; x \; D$$

Whereby:

S … Severity of failure mode

P … Probability of failure mode

D … Detectability of failure mode

Equation 4-1

FMEAs are often combined with a Fault-Tree-Analysis (FTA), which focuses on a probabilistic analysis of all circumstances possibly leading to the undesired event. The FMEA technique depicts an inductive approach with low interdependencies whereas the FTA approach outlines a deductive technique focusing on interdependencies of the failure mode analysis.

Based on the traditional approach, there are modifying expansions thereof. One example applied in the automotive sector is the Failure-Mode-Effect-and-Detectability-Analysis (FMEDA), which includes and focusses on the diagnostic coverage. In today's aerospace industry the basic analysis is modified by additionally considering parameters describing the criticality of a failure mode, also known as Failure-Mode-Effect-and-Criticality-Analysis (FMECA). In this context, criticality is defined as the ratio between the probability of a specific failure mode against the severity of the considered failure mode (Jertz 2005).

The most widely used standard for FMEA projects is the Military Standard MIL-STD-1629A. Due to the complexity and criticality of military systems it provides a reliable foundation on which it is possible to perform FMEAs on a variety of systems. It also contains formulae for predicting the failure rates of electrical and electronical failure rates whose coefficients are based on accelerated life tests. Other equivalent standards are e.g. SAEJ 1739 for automotive applications or the SMS Regulation 800-31 for aerospace structures.

As shown in Table 4-1, a variety of empirical wind turbine reliability surveys and databases are known. Also, several PhD projects in Europe were concerned with reliability analysis of on- and offshore wind turbine systems – e.g. (Andrawus 2008), (Karyotakis 2011), (Besnard 2009), (Shafiee et al. 2013),– (Luengo and Kolios 2015) to name a few. Figure 4-7 presents a consolidated reliability overview for on- and offshore wind turbines in Europe based on the current scientific findings.

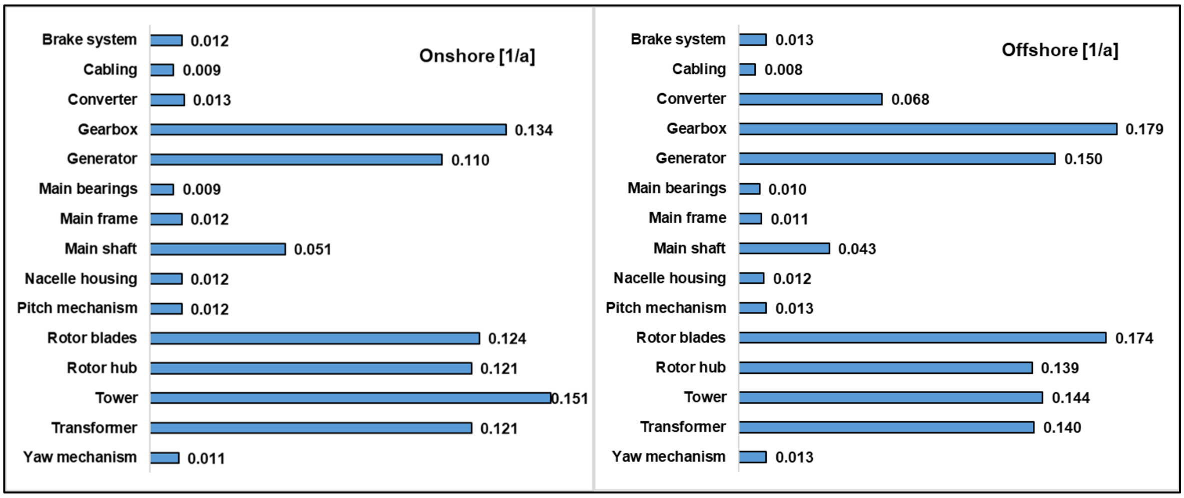


Figure 4-7: Consolidated failure rates of an on and offshore wind turbine system

Considering the annual failure rate as an equivalent for the occurrence probability of specific failure modes in wind turbine sub systems, it can clearly be derived that among the rotor hub, generator, transformer, rotor blades and gearbox, the turbine supporting structure is one of the most critical sub systems.

Applying the described classic FMEA pattern with a panel of wind turbine experts lead to the following results. Figure 4-8 shows a classical risk matrix in which the calculated RPN (Risk priority number) values are matched with the underlying failure occurrence probability of the specific sub system.

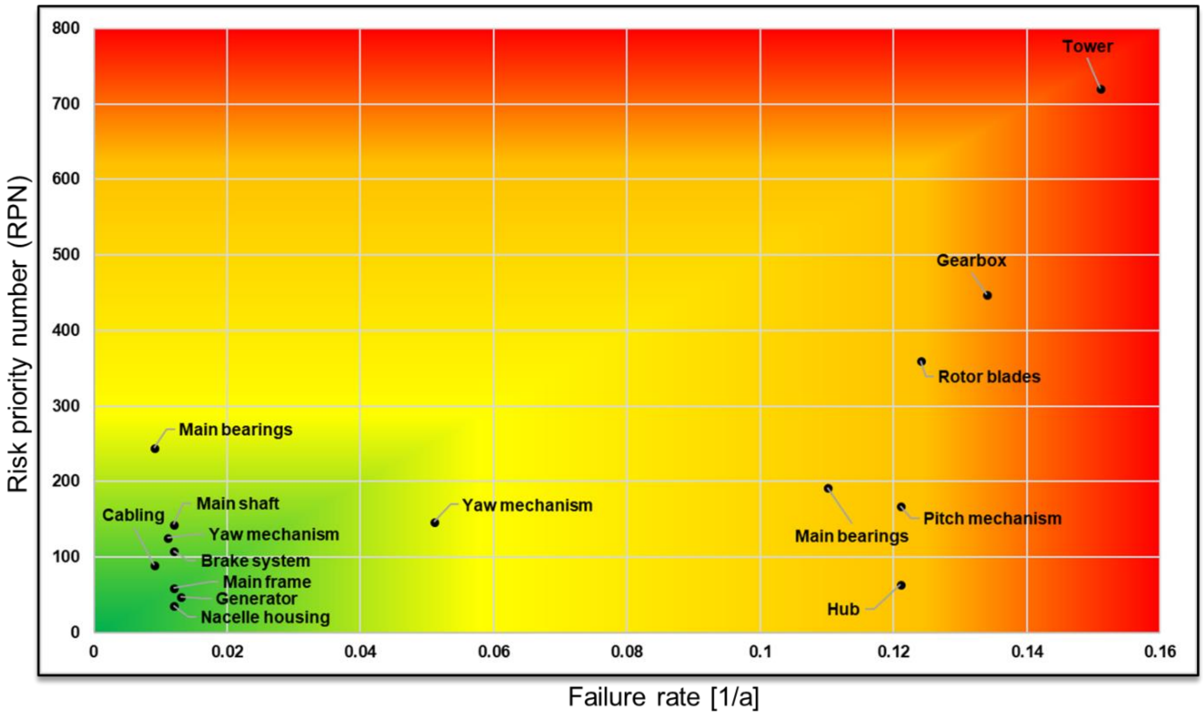


Figure 4-8: FMEA risk matrix of an onshore wind turbine system

Figure 4-9 clarifies the sub system contribution to the overall risk priority number of the onshore wind turbine system, based on which it is possible to cluster the sub system criticality. In the expert panel it was decided, that sub systems contributing up to 70 % of the overall RPN are defined as A-critical, the following 20 % as B-critical and the remaining 10 % as C-critical.

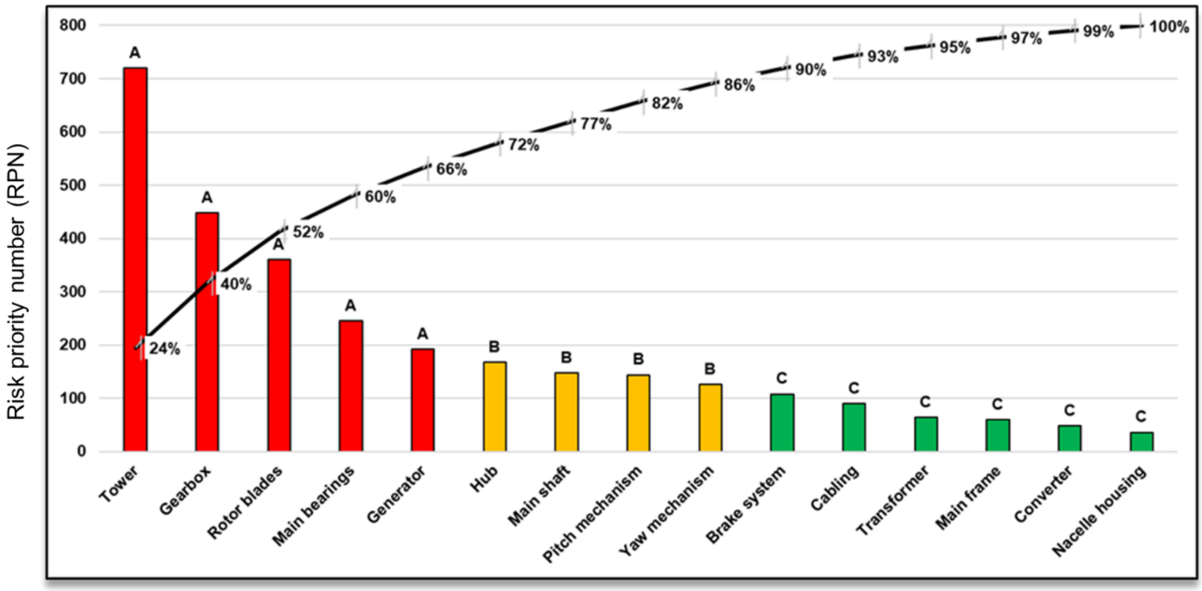


Figure 4-9: FMEA pareto analysis of an onshore wind turbine system

Applying the same scheme on the offshore wind turbine system leads to the results which are depicted Figure 4-10. In comparison to the onshore system, the wind turbine tower is occupied with a lower annual failure rate in the offshore system. This might be traced back to the fact that offshore tower design gained profit from the operational experience gained in the onshore applications. However, it could also be that the smaller amount of operational experience and empirical data only represent an early picture of the reliability behavior of offshore wind turbine towers.

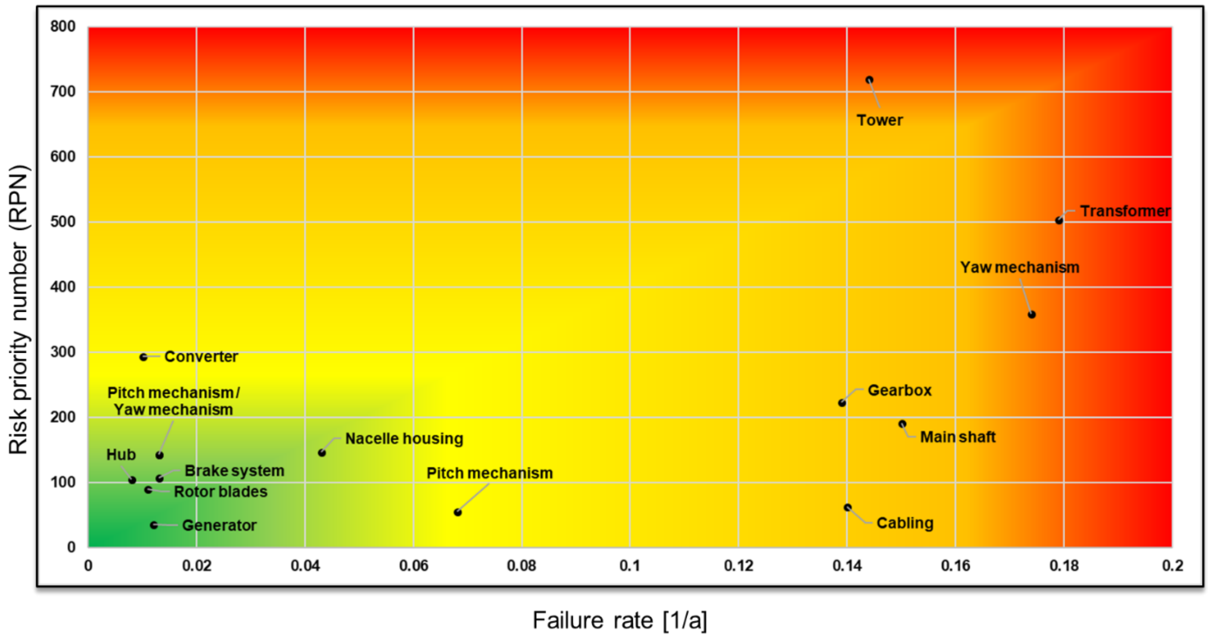


Figure 4-10: FMEA risk matrix of an offshore wind turbine system

As Figure 4-9 depicts for onshore wind turbine systems, Figure 4-11 clarifies the sub system contribution to the overall risk priority number of an offshore wind turbine system.

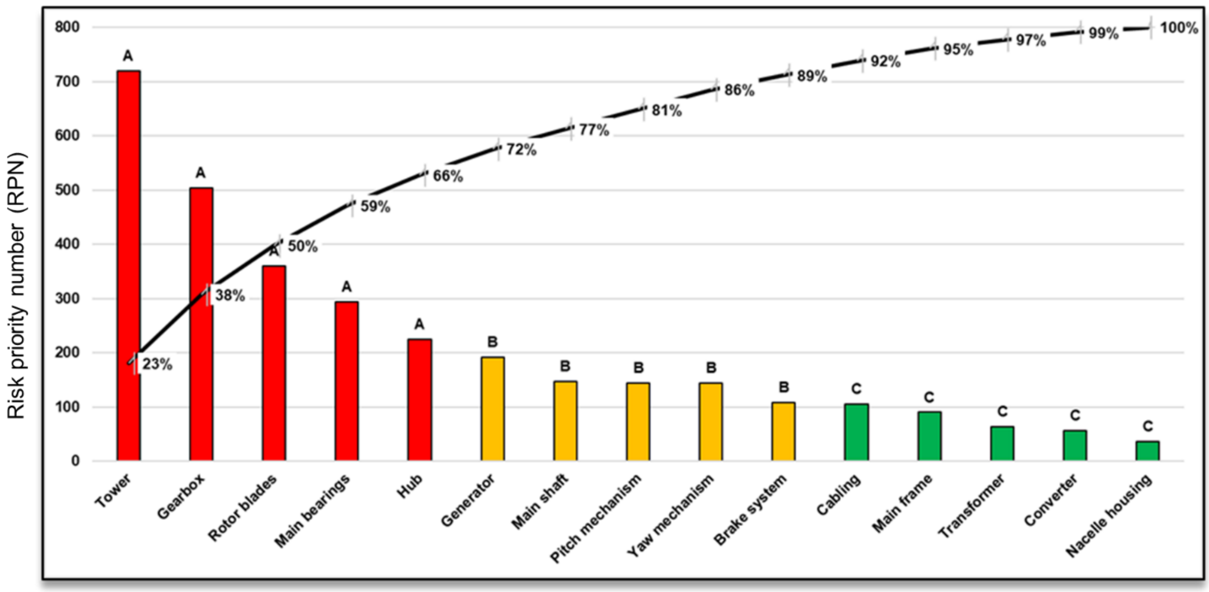


Figure 4-11: FMEA pareto analysis of an offshore wind turbine system

The provisional result of a risk analysis applying a classic FMEA analysis leads to the conclusion, that tower, gearbox, rotor blades, main bearing and generator are the most critical systems for which a condition-based maintenance strategy might be most accurate.

However, all classic risk analysis approaches based on a FMEA methodology show critical weaknesses. First and foremost, the relative importance between the three parameters is not considered. Furthermore, different combinations of parameters may lead to the same risk-priority number, however hidden risk implications can be entirely different. Also, important interdependencies among various failure modes and effects are not considered. Further on, the RPN calculation considers only three risk factors, mainly in terms of safety. Last but not least, the three risk factors are difficult to be precisely evaluated on a quantitative scale (Liu et al. 2013). However, Tavner worked on a wind turbine specific FMEA (Tavner et al. 2010). Especially concerning a practical application in analyzing operation and maintenance risks of a wind turbine system, the following drawbacks can be noted:

- RPN values are not informative and discrete enough from the perspective of criticality in the operation and maintenance life cycle phase of a wind turbine system
- Heterogeneity of wind turbine systems in the market is high, comparing RPN values with different wind turbines is not possible
- RPN values are not continuous and their distribution often shows to be “unnatural”
- The traditional FMEA methodology considers only three risk factors in terms of safety, important economic aspects on the O&M phase – such as production losses, manpower, and logistic cost – are not considered and the result often does not represent the true risk priorities of the wind turbine operator

4.3.3 HOLISTIC WIND TURBINE COST-BASED RISK ANALYSIS APPROACH

Considering the weaknesses of the traditional FMEA methodology used to analyze operating wind turbine systems to establish risk-based maintenance strategies, this section will introduce a new holistic approach to evaluate systematic risks in a wind turbine system as a first quantitative step in finding the optimal maintenance strategy. The Cost-Based-Risk-Analysis (CB-RA) focusses mainly on the cost consequences of a failure, which also represents the primary concern of wind turbine operators considering operational risks. Kmenta and Ishii (2000), Shafiee and Dinmohammadi (2014) and Kahrobaee and Asgarpoor (2011) developed similar approaches.

The cost consequences of failure are expressed by a positive value including all costs associated with a failure case, in particular: repair and replacement cost, logistics, transportation, manpower and opportunity cost evoking from production loss.

The cost consequences of a failure mode i can be expressed as follows:

$$C_i = C_{i,R} + C_{i,L} + C_{i,M} + C_{i,P}$$

Equation 4-2

Whereby $C_{i,R}$ summarizes the cost of repair or replacement of the specific sub-assembly which needs to be repaired or replaced due to the failure. $C_{i,L}$represent the logistic cost of equipping the maintenance crew and ordering the spare parts as well as special repair or replacement equipment like a heavy loads transport or assembly equipment. $C_{i,M}$bears the necessary manpower cost of the specific maintenance task of the respective failure case. Finally, $C_{i,P}$cover the expected opportunity cost of the production loss resulting from the turbine's failure case. $C_{i,P}$ can be expressed and calculated in accordance with the respective downtime of the relevant failure case $t_{d,i}$ and the capacity factor w of the wind turbine.

$$C_{i,P} = t \cdot c_{PL}$$

Equation 4-3

Whereby c_{PL} is expressed by:

$$c_{PL} = W \cdot EP \cdot w$$

Equation 4-4

W represents the nominal electrical capacity of the wind turbine, EP integrates the current unity cost of energy.

The probability of occurrence of the specific failure mode is a positive value < 1 and can be calculated as follows:

$$O_i = \frac{\lambda_i}{\sum_{i=1}^{k_f} \lambda_i}$$

Equation 4-5

Whereby:

k_f … total number of potential and known failures

Respectively:

$$O_i = \lim_{s \to \infty} \frac{Number\ of\ failures\ resulting\ from\ failure\ mode\ i\ in\ time\ period\ [0, s]}{Number\ of\ total\ failures\ observed\ in\ time\ period\ [0, s]}$$

Equation 4-6

It is assumed, that the wind turbine's main sub-assemblies are arranged in series and have no redundancies.

Data sources can be empirical field failure data bases like the WindPool-data base (Jung 2016), or specific failure data from the operator's CMMS.

Furthermore, the third parameter is the not-detection-probability of the specific failure mode, which also will be a positive value < 1 and expresses the ratio between the overall failures in the sub-system and the detected failure modes before occurrence in the specific sub-system:

$$ND_i = \frac{N_{i,F}}{N_{i,F} + N_{i,D}}$$

Whereby:

$N_{i,F}$ = sum of of actual failures

$N_{i,D}$= sum of of detected failure before occurrence

Equation 4-7

Finally, the Cost-Based-Risk-Priority-Number $CB{-}RPN_i$ of each failure mode i constitutes as expressed below:

$$CB{-}RPN_i = O_i \cdot C_i \cdot ND_i$$

Equation 4-8

The most suitable maintenance and operation cost data source are the surveys from DEWI (German for: Deutsches Windenergie Institut). The most comprehensive one was carried out by Neumann et al. (2002).

In comparison to the results of the FMEA analysis in chapter 4.3.2, the cost-based risk analysis results are more differentiated according to their cost perspective. For both, the onshore and offshore wind turbine systems, the supporting structure is clearly exposed as the most critical sub-system when it comes to cost-consequences.

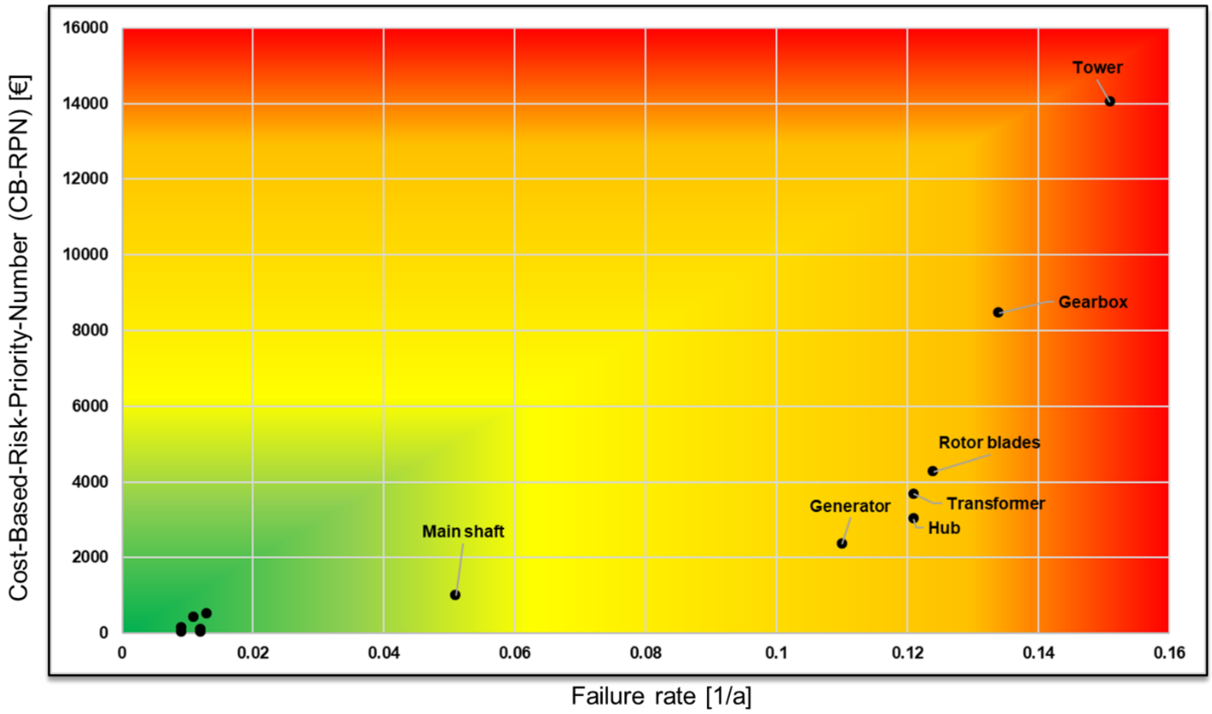


Figure 4-12: CB-RA risk matrix of an onshore wind turbine system

The cost-based risk analysis matrix of an onshore wind turbine system is displayed in Figure 4-12. Looking at the pareto analysis (Figure 4-13), tower, gearbox and rotor blades are A-critical system in an onshore wind turbine system and should be integrated in a condition-based maintenance strategy at least. Transformer and hub failures induce medium-critical cost consequences for the operator. The remaining sub-assemblies induce only minor risks from a cost-perspective.

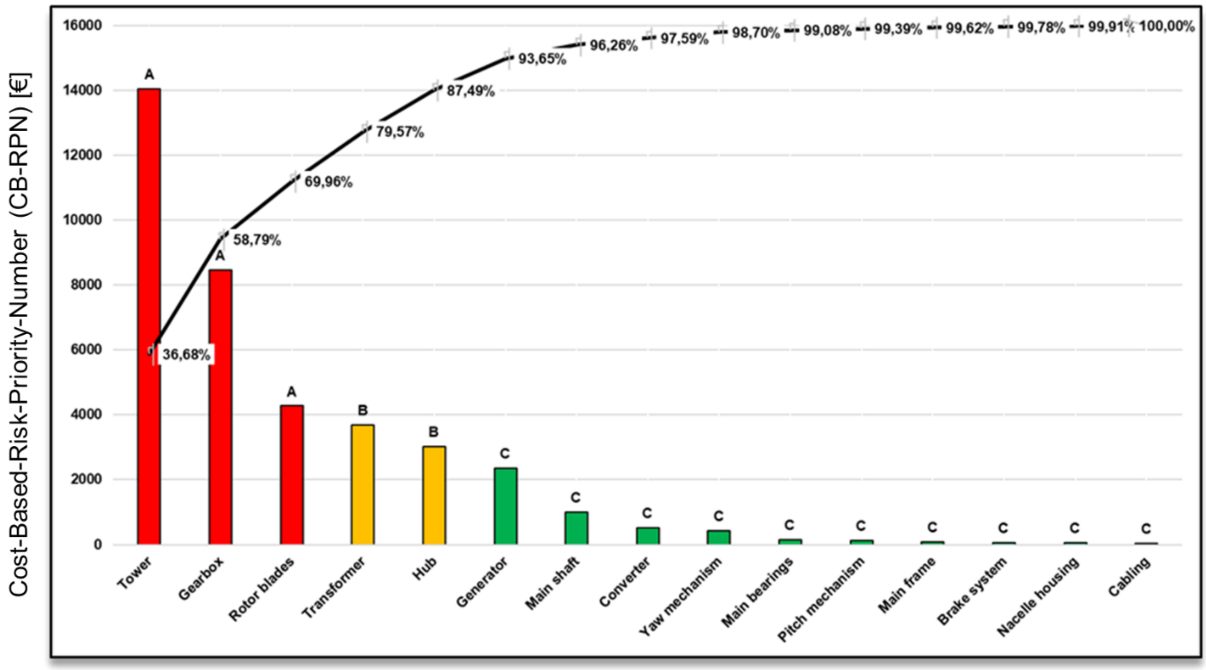


Figure 4-13: CB-RA pareto analysis of an onshore wind turbine system

Looking at the offshore wind turbine system, all sub-assemblies rank considerably higher in their cost-consequences, Figure 4-14.

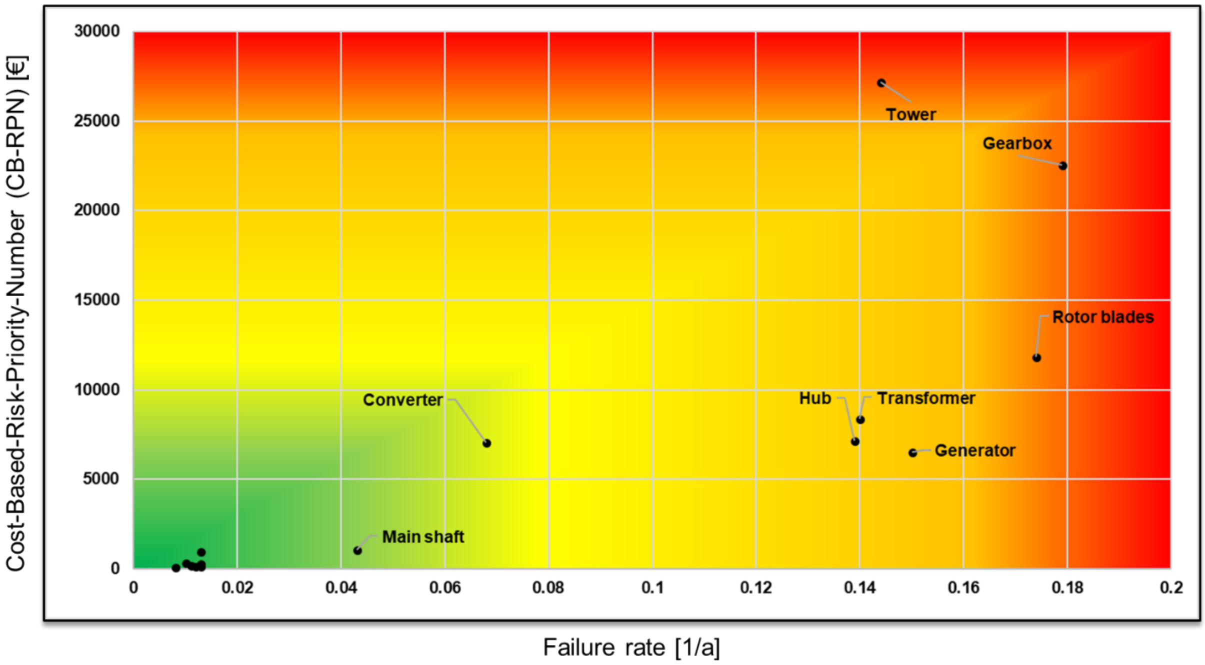


Figure 4-14: CB-RA risk matrix of an offshore wind turbine system

Similar to the onshore system, tower, gearbox, and rotor blades are the most critical systems in an offshore wind turbine system, Figure 4-15.

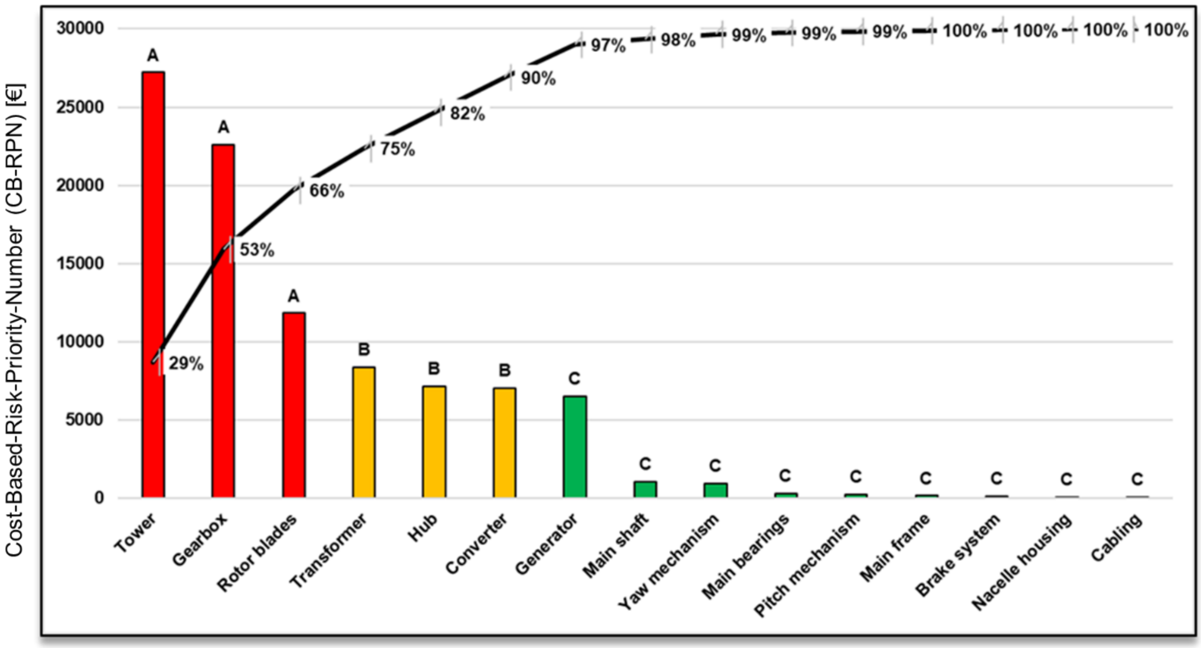


Figure 4-15: CB-RA pareto analysis of an offshore wind turbine system

To compare the different types of wind turbines from a criticality perspective, the annual cost-based risk priority number should be considered - $ACB{-}RPN_i$. The annual $ACB{-}RPN_i$ for a wind turbine system with k potential / known failure modes is defined as:

$$ACB{-}RPN_i = \sum_{i=1}^{k} E(N_{i,FV}) \cdot ACB{-}RPN_i,$$

Equation 4-9

whereby $E(N_{i,FV})$ is the expected number of failure vulnerabilities per year. Failure vulnerabilities are defined as possible failures and thus can be used as criticality measure. Failure vulnerabilities include the number of actual failures and the number of detected possible failures prior to their occurrences, for one year. These risks of failure may be detected by monitoring and inspection techniques. Each sub-assembly $ACB{-}RPN_i$ is multiplied by its failure vulnerability as a weighting factor.

Since the primary operational risks of a wind turbine system are identified, the next step is to define general risk mitigation strategies. Figure 4-16 shows the allocation of maintenance strategy families introduced in chapter 3.2 to the operational risk categories. A-critical components are to be operated in a combination of predictive maintenance, using predictive and probabilistic estimation techniques combined with high resolution structural health condition monitoring systems. If the maintenance analysis comes to the conclusion that available predictive methods will not lead to a significant risk mitigation or if they are not assumed to be economical within the asset’s service life, maintenance planning might as well consider triggering constructive modifications of the wind turbine within a feasible scope. If neither of the above is applicable, the operators will have to consider a plant shutdown. B-critical components are most suitable to be operated under an intermediate maintenance strategy family, applying data analysis techniques which allow to operate in a preventive manner. However, already existing operational data – e.g. SCADA-data and inspection protocols - should be used in a primary focus before installing additional sensor systems. Finally, C-critical systems imply a relatively low risk share to the system’s risk portfolio, therefore components within this group can be operated under standard scheduled maintenance plans. If some components are redundant or a failure of their primary function will not lead to immediate operational, environmental, or safety issues, and repair cost and time are negligible, they can also be managed in a corrective maintenance strategy.

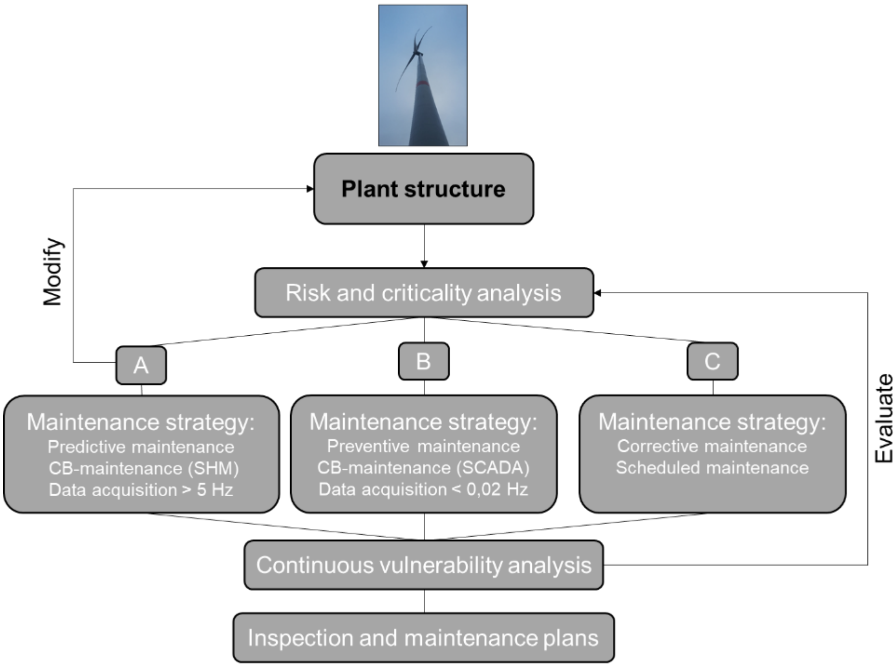


Figure 4-16: Preliminary maintenance strategy definition

It is important to state that these maintenance strategy allocations are only preliminary, based on a cost-driven quantitative risk analysis. The performance of the chosen maintenance strategy combinations must be evaluated continuously along significant key performance indicators (KPI). Moreover, wind turbine operators should establish a periodic vulnerability analysis, which serves to identify, monitor, and manage upcoming operational risks continuously and transfers upcoming issues back into the maintenance risk analysis. Lastly, the defined maintenance strategies must be transferred into the operative inspection and maintenance plans containing all relevant information and resources to carry out the defined maintenance strategy with the operational personnel.

Figure 4-17 allocates the analyzed wind turbine sub-systems to the respective maintenance strategy for an onshore wind turbine system. The most risk-inheriting sub-system in both onshore and offshore wind turbine systems is represented by the wind turbine tower or wind turbine supporting structure.

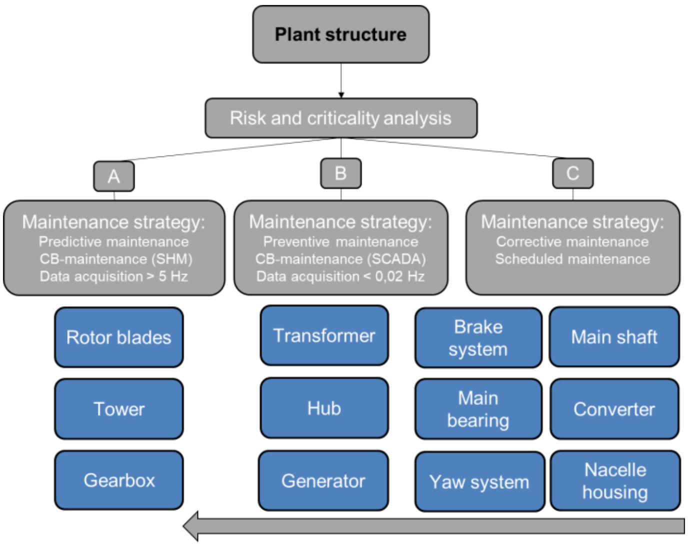


Figure 4-17: Risk-based allocation of maintenance service strategies

4.4 QUALITATIVE MAINTENANCE STRATEGY DECISION PROCEDURE

To answer research question **RQ 4**, the following section displays the findings:

What can a qualitative maintenance strategy decision framework look like?

Based on the described qualitative risk analysis, the following paragraph introduces a specific service strategy decision procedure on a qualitative level. The first step is to define the asset system functions in their operating context. Conceptually, there are two categories. Primary functions describe the primary goal of the asset's existence, e.g. to convert kinetic wind energy into electrical energy. Secondary functions describe requirements of the asset concerning safety, control, structural integrity, economy, efficiency of operation, and compliance with regulations. Furthermore, functional failures will be introduced. Functional failures describe the failure of fulfilling a pre-defined function with a specific performance level. Subsequently, failure modes will be introduced. A failure mode analysis investigates which events can cause pre-defined failure modes. First and foremost, the failure mode analysis will incorporate failures caused by deterioration and wear and tear. However, the failure mode analysis will also include failures occurring due to human error or design flaws. The failure mode analysis should be done in detail and substantially in a group of experts. To ensure not to treat symptoms instead of failure root causes, the group of experts is guided by a moderator, which has deep methodological expertise. However, care must be taken to balance between a very detailed analysis and wasting important time (Geiss and Guder 2017, 2018).

The consequences of a failure are the main measure concerning which maintenance action will be connected to the specific failure mode. Maintenance engineers must be conscious that failures in themselves cannot be prevented, all derived measures have the focus to avoid or reduce the consequences of a failure. The different failure consequences can be subdivided into four different categories:

1) **Hidden failure consequences;**
With no direct impact, but expose the system to multiple failure with serious consequences e.g. protective devices
2) **Safety and environmental consequences;**
With a high possibility of injuring or killing someone or
with a high possibility of environmental consequences
3) **Operational consequences;**
With a high possibility of affecting production in a negative way, production losses, and direct cost or repair
4) **Non-operational consequences;**
Affecting neither safety nor production; involve only direct cost of repair

If a failure can lead to multiple consequences, the failure consequence with the highest severity rating should be considered primarily. Considering the detailed maintenance strategy allocations, maintenance engineers should focus on the maintenance activities with the most effect on the wind turbine system, it can however not be the goal to find a technological solution for every identified problem or deviation.

Based on the described failure categories, the following decision rules can be applied in a practical environment:

- **Hidden failures**

  A predictive task is worth doing if it reduces the risk of multiple failures. If such a task cannot be found, the strategy should consist of preventive failure finding monitoring and inspections tasks. If suitable failure finding tasks cannot be found, the item under consideration must be redesigned or modified.

- **Safety/environmental failures**

  A predictive or preventive task is worth doing if it reduces the risk of failure on its own to a very low level. If such a task cannot be found, the item under consideration must be redesigned or the operational process must be adjusted.

- **Operational failures**

  A predictive or preventive task is worth doing when the total cost over the remaining service life is less than the cost of the predicted operational consequences and the cost of repair in the remaining service life. If this is not the case, maintenance engineers might consider a corrective or run-to-failure service strategy. If none of the above is acceptable, the item under consideration must be redesigned or modified.

- **Non-operational consequences**

  Predictive or preventive tasks must be justifiable from an economic point of view, as stated for operational failures. If not, a run-to failure or corrective maintenance strategy might be considerable. If the expected repair costs are too high, redesigning or modifying the item under consideration should be evaluated.

The functional classification of the asset under analysis is a premise and the first step in the decision logic. In this conception, a function consists of an object, a verb, and a related performance or capability measure. Quantitative performance standards work best, qualitative performance statements like “as best as possible” should be avoided or taken with care. In some cases, it might be impossible to find a suitable quantitative performance parameter, thus it is recommendable to define a qualitative scaling of the performance state. Furthermore, it can be distinguished between absolute performance standards – e.g. containing liquid – and variable performance standards with upper and lower limits, e.g. a reliability level.

The functional asset classification is based on two different types of functions, primary functions and secondary functions. Primary functions describe the main reason for which an asset exists. The asset function mechanism can be drawn in a block diagram to examine the asset from a systems-engineering approach. Often assets have more than one primary function. Furthermore, systems are often so complex, that a sub-system review is necessary to understand and factor all relevant system effects in the analysis. Primary functions are sometimes connected in a serial way and dependent on each other. Secondary functions support or enable the operations of the asset’s primary functions. Different categories of secondary functions can be used for classification, e.g. environmental integrity, protection, efficiency, safety, and structural integrity especially for large complex structures with multiple load bearing components. Protective, safety, or structural integrity relevant components often need more maintenance attention than the devices they are protecting. The loss of a secondary function can have severe consequences, often worse than the loss of a primary function.

The functional classification of an asset is very important; since components of an asset fulfill different functions they can also fail in different ways, and thus maintenance strategies must also be defined and customized on a functional level.

The asset’s functional failures were listed, and the coherent failure modes were recorded accordingly. Thus, the failure mode level states the field of activity for maintenance actions or strategies. The goal trying to identify all possible failure modes in the system analysis to avoid expensive reactive maintenance actions and to deal with failure events before they occur. However, balance must be taken with the level of detail in the system analysis. A good measure is to break down the granularity of the system to the point of having enough information to define a suitable maintenance strategy. A holistic risk analysis should deal with all relevant failure modes, from design flaws to human errors. However, one of the most controllable failure modes is represented by the falling capability or deterioration of a component. Mechanical deterioration is caused by stresses, lowering the resistance of a component. At some point in the component’s life – assuming no maintenance action – the resistance will drop at a level where the component will no longer resist the stresses and fails. Several physical and empirical laws are available to describe the deterioration process. Considering the failure effects, the decision logic procedure is oriented on the following questions:

- What evidence can be found of the failure’ occurrence?
- How is the failure mode a threat for safety?
- How does the failure mode affect operations?
- What physical damage is caused by the failure mode?
- Which repair actions should follow the failure mode?

The effect analysis is done under the assumption of a green field, assuming no actions behind the failure modes.

Consequently, analyzing field data is often difficult, as it often describes the measures taken, but not the root cause for the failure.

Furthermore, it is also important to understand that each failure mode has a different PF interval corresponding to the PF interval introduced in chapter 3.2 and will require a different combination of monitoring and inspection tasks. Figure 4-18 depicts the failure mode of a generic bearing in the PF-diagram.

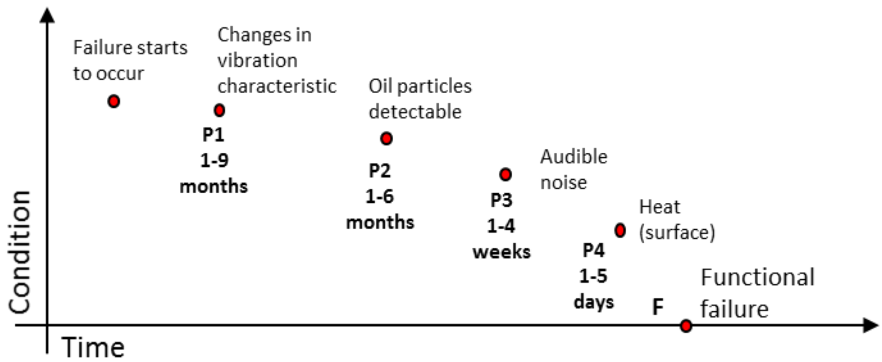


Figure 4-18: Failure mode of a generic bearing in the PF-diagram – adapted from (Moubray 1995)

If a physically suitable monitoring and inspection technique is found, maintenance engineers must consider the practical environment in which the technique should be applied. For example, a bearing can be buried deep in the gearbox, making it difficult to monitor its vibration characteristics. Debris particles can only be detected when the lubrication system is suitable. Background noise might make it impossible to detect the noise made by the failing bearing.

Figure 4-19 describes the process of the developed qualitative service strategy decision procedure graphically. The turbine system is subdivided in its primary and secondary functions. Based on this level, all relevant failure modes of the involved sub-systems and parts must be deducted. The next level of analysis considers all relevant failure causes of every deducted failure mode. Subsequently, the respective failure modes can be evaluated concerning their induced failure consequences. According to the applied risk-evaluation scheme, risk mitigation tasks are to be defined. Generally, there are two categories of risk mitigation tasks, modification of the wind turbine system and definition of a pro-active maintenance and service strategy. Based on the failure cause level of each failure mode, one can derive suitable monitoring and inspection tasks, which could detect the relevant failure cause early and enable the maintenance engineers to derive preventive measures. The complete system analysis can be performed on a type-specific basis with a weighting factor for the actual location specific loading of the wind turbine. All derived actions, data, and tasks relevant for maintenance planning will have to be integrated in a Maintenance Master Plan (MMP), which specifies the service strategies from a maintenance planning point of view and allocates the respective resources. Typically, an MMP is set up for a duration of one year. As last and sustainable step, all gathered data from this process should be integrated in a so-called Computerized Maintenance Management System

(CMMS), which acts as an assisting software platform for all concerned in the operation and maintenance phase of a wind turbine system and enables continuous performance and vulnerability analysis methods during the service life of a wind turbine system.

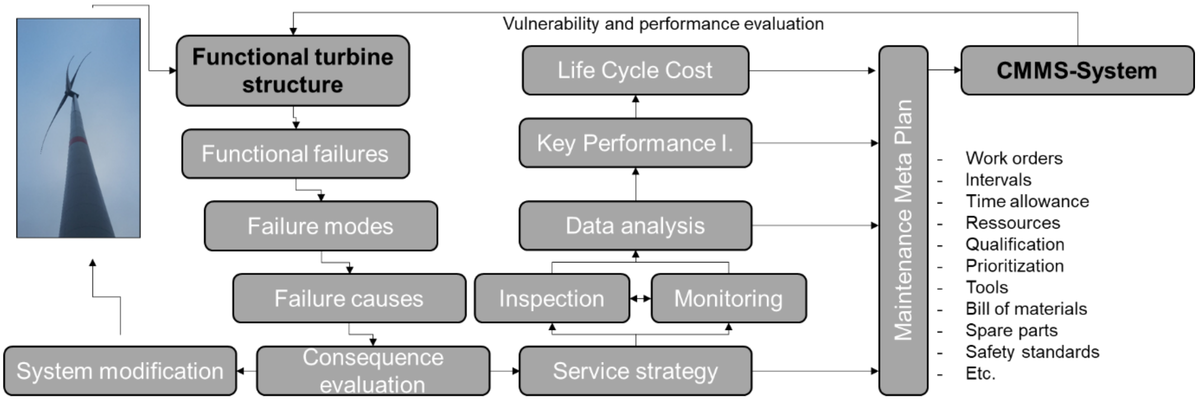


Figure 4-19: Flowchart of service strategy decision procedure

Statistically the two most relevant deterioration mechanisms for a wind turbine supporting structure are corrosion mechanisms and wear or fatigue crack growth mechanisms. Considering normal environmental conditions and a reasonable implementation of corrosion protection, the wear mechanisms are the most critical deterioration mechanisms of the structural system (see chapter 4.3.1).

In engineering, there are models for describing the specific fatigue mechanisms which cause wearing of a structural element. However, these models inherit implied model uncertainties. Those model uncertainties can be reduced by in-field inspection data. Under this aspect, NDT methods are an effective risk mitigation measure for existing structures.

4.5 MONITORING AND INSPECTION DATABASE FOR WIND TURBINES

To answer research question **RQ 5**, the following sections display the findings:

Which damage detection and data analysis techniques are most suitable for a holistic asset management concept for wind turbines?

One core part of the IAMS-concept is a holistic damage detection database which was developed in the scope of the dissertation and is the result of an extensive research in the field. The database is programmed in MS Excel and uses VBA-code for data analysis. However, the database can also be connected or integrated into a CMMS system. Figure 4-20 displays the scope of the database graphically – finding optimal combinations of monitoring and inspection techniques for wind turbine health monitoring.

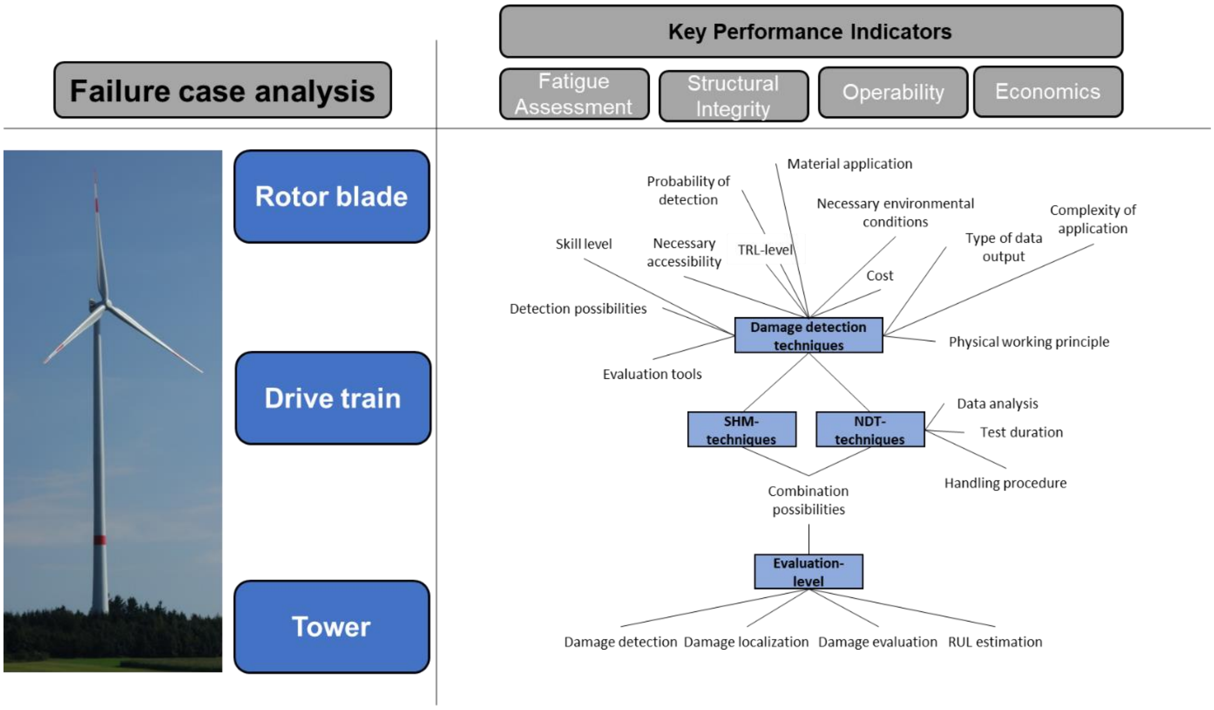


Figure 4-20: Structure of the IAMS damage detection technique database

Since the early 2000s, condition and structural health monitoring systems for wind turbines have been emerging. This development was mainly due to repeated severe gearbox failures of early wind turbine drive train concepts and a resulting pressure from the insurance industry to define technology which enables the operators to prevent such severe failures as standard requirement for their insurance contracts.

Generally, wind turbine monitoring can be subdivided into the operational monitoring purpose and the respective sampling rate at which the systems gather monitoring data. A general summary can be found in Sheng (2013). Worden introduced fundamental axioms of structural health monitoring and inspections, which will be applied here (Worden et al. 2007).

Table 4-3: General summary and overview of wind turbine monitoring technologies

Operational purpose	Typical sampling rate
Offline diagnosis of drive train components, e.g. monitoring of bearings and gear boxes	10 kHz
CM (Condition Monitoring) for generator, drive train and rotor blades, e.g. vibration monitoring	< 35 Hz
SHM (Structural Health Monitoring) monitoring of tower and fundament, e.g. acceleration and strain measurements	< 5 Hz
SCADA (Supervisory Control and Data Acquisition) signals and alarms of the wind turbine control system, e.g. system status, rotor speed, electrical power, etc.	< 0.001 Hz

The following passages will focus on the most important damage detection techniques for wind turbine systems in the scope of the dissertation.

4.5.1 SCADA – SUPERVISORY CONTROL AND DATA ACQUISITION

SCADA-systems are a standard installation in large wind turbines and wind farms. SCADA-systems are also operative in other industrial applications, such as coal-fired or nuclear power plants and offshore oil platforms or other industrial assets. Data is collected from individual wind turbine controllers.

The number of signal channels varies considerably between turbine manufacturers as well as between turbine generations. Typically, the sampling rate is a ten-minute-average value. However, higher sampling rates are available in younger turbine generations. In some cases, it is possible to access more detailed levels of the SCADA-systems with sampling rate below one-minute-average values. A typical set of standard SCADA-channels constitutes as follows:

- Wind speed
- Wind direction
- Active power
- Reactive power
- Ambient temperature
- Pitch angle
- Rotational speed (rotor and/or generator)

Comprehensive SCADA data sets also include minimum, maximum, and standard deviation values of every ten-minute-step. Newer turbine generations often provide hundreds of signals, including temperature measurements from different positions, pressure values from different lubricant systems, electric quantities, e.g. line currents and voltages. In some wind turbine models, an integrated tower vibration measurement is available.

A comprehensive review of different approaches of possible SCADA-data analysis methods is provided in Wilkinson et al. (2014). Fundamentally, one can group the data analysis approaches in three different groups; signal trending, physical models, and artificial neural networks.

- Signal trending

Comparing SCADA-data to corresponding SCADA-data from other turbines in the same wind park can enable first analysis steps and provides a historical comparison throughout the whole wind park.

- Artificial Neural Networks (ANN)

ANNs are trained to model the normal behavior of a wind turbine. The network trains with data covering the complete operation behavior of the wind turbine to detect abnormal operational behavior. Figure 4-21 shows the general principle of ANNs graphically. It is of crucial importance to ensure that the training data proves to be representative for a normal turbine behavior (Schlechtingen and Ferreira Santos 2011).

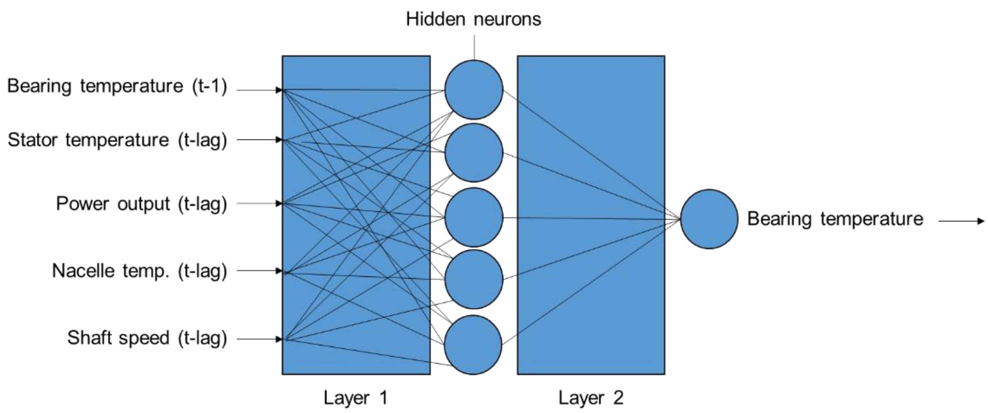


Figure 4-21: General principle of ANNs for wind turbine monitoring – adapted from (Schlechtingen and Ferreira Santos 2011)

- Physical models

Physical models use regression models which are based on the underlying physical process. The models use SCADA-data signals defined as model input for predicting the quantity of interest under specific operation conditions. Deviations between the predicted value and the actual SCADA-data value can be used for analysis and preventive damage detection. Abdusamad et al. (2013) described such an application for a bearing degradation problem. Figure 4-22 graphically describes the regression model for the drive train.

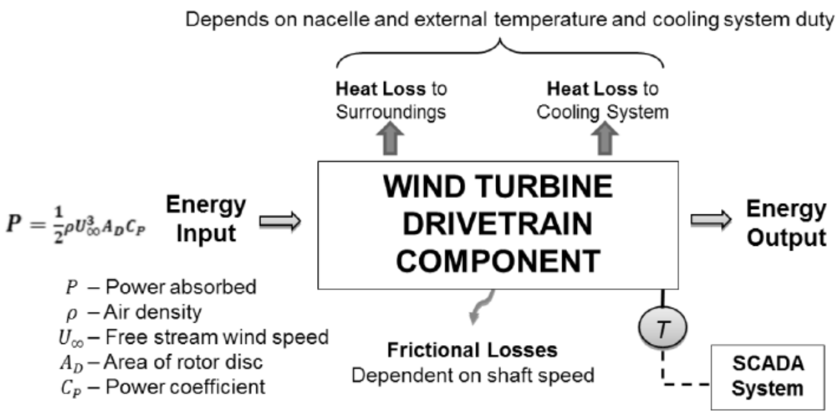


Figure 4-22: Regression model of Abdussamad for drive train monitoring (Abdusamad et al. 2013)

Wilkinson conducted a study on historical data with 472 wind turbine operational years – 24 out of 36 failures were detected using SCADA-data analysis applying physical models (Wilkinson et al. 2014).

SCADA-systems were not designed explicitly for failure detection. However, it is worthwhile using the information basis SCADA-data inherits to investigate the health status of the wind turbine system. Furthermore, SCADA-data can be an important source of information for data-fusion methods using data from multiple sensors and different monitoring systems. The combination of all data streams will allow unique interferences. SCADA-assisted monitoring can provide additional value for correlating and validating CMS and SHM systems, e.g. information on bearing temperatures in drive trains, pitch angles of rotor blades, and wind speed data.

4.5.2 VIBRATION-BASED CONDITION MONITORING SYSTEMS

Condition monitoring systems have the main purpose of monitoring rotating machinery equipment in wind turbine drive trains. The advent of condition monitoring systems for wind turbines was caused by pressure from the insurance industry from 2003 on (Gellermann and Walter 2003). CM-systems (CMS) for wind turbines differ in sensor measurement ranges, number of installed sensors, location of installed sensors, data collection system, and data assessment methods. All CMS applied on operative wind turbines must be certified by the relevant authority (Dalhoff and Muuß 2009).

Vibration-based CMS have emerged as the standard monitoring technology. In most applications, the vibration-based system is combined with an oil particle counting system.

Vibration-based CMS are established on the assumption that most damage in rotating machinery leads to abnormal vibration patterns and that each damage generates a unique vibration pattern. Figure 4-23 depicts time- and frequency-domain-based approaches for vibration monitoring.

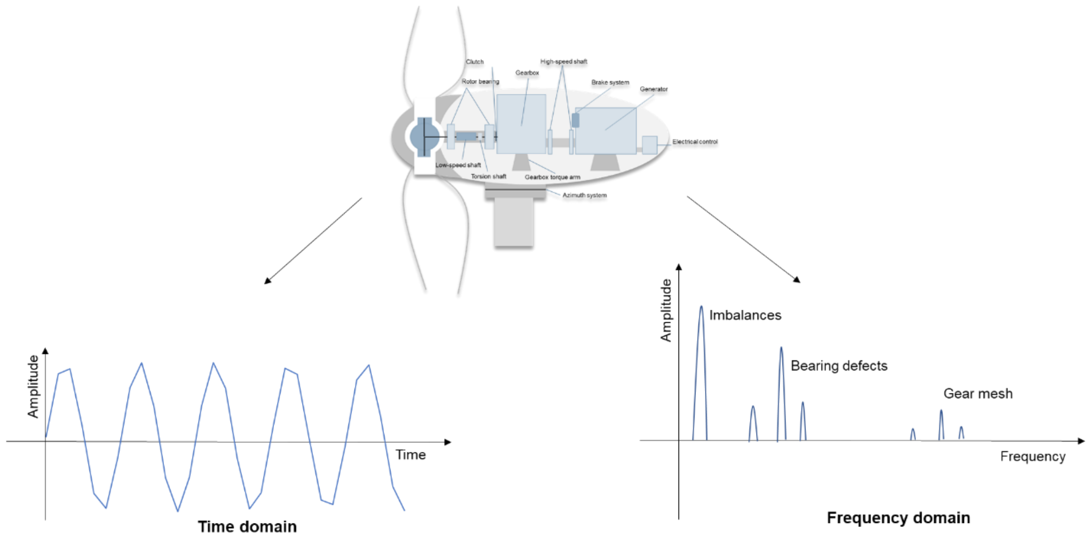


Figure 4-23: Time- and frequency domain-based approaches

Sensors applied in vibration-based CMS range from classic accelerometers, velocity and displacement transducers. In most cases accelerometers are installed on different positions in the drive train, e.g. on the main bearing, the generator bearing or the gearbox. Thus, different accelerometers must be used from low frequency ranges to high frequency ranges. Operational frequencies in the drivetrain system range from 0.1 Hz to 10 kHz. In this set-up, the dynamic range and sensitivity of the sensors applied must be considered, acceleration amplitudes in the low frequency range can be very small. ISO 133373-1 provides a guideline for choosing the right sensor for the specific application and use case. ISO 10816-21 provides criteria and recommendations for the measurement and characterization of vibrations of wind turbine components. Specific threshold values are evaluated statistically for many wind turbines and can serve as a basis for designing a CM-system.

ISO 61400-25-6 states a standard nomenclature for sensor types used in wind turbines – which is not limited to vibration sensors. It is recommended to bin vibration data according to the active power level of the wind turbine, because the vibration characteristic of a drive train is more dependent on the active power production of the drivetrain then on wind speed.

General requirements and recommendations for sensor positioning within the drive train system of a wind turbine is given in the GL certification guideline for CMS (Dalhoff and Muuß 2009). However, the recommendations are not very specific due to the large variety of drive train designs and wind turbine types. Minimum requirements for number, position, frequency range, and orientation are summarized in Table 4-4.

Table 4-4: Minimum requirements for vibrational sensors installation on wind turbines

Component of the wind turbine	Necessary number of sensors per component	Direction of measurement	Frequency range
Rotor blade	2	In rotor axis direction and transversal to the rotor axis	0.1 Hz … > 10 kHz
Rotor bearing	1 (+1 optional)	Radial + axial	0.1 Hz … > 10 kHz
Gear box	4 + 1	Radial + axial	0.1 Hz … > 10 kHz at low speed shaft 10 Hz … > 10 kHz at high speed shaft
Generator bearing	2	Radial	10 Hz … > 10 kHz
Nacelle	2	Axial in wind direction and transversal to the axial direction	0.1 Hz … > 100 Hz

As a general requirement, the operational vibrations of the drive train should be led as directly as possible to the vibrations sensor of the CM-system and it should see all relevant frequencies at that specific spot. In planetary gearboxes one vibration sensor per stage should be installed, at the ring gear and at the level of the sun gear. Early fault detection in planetary gearboxes is a particular challenge, as vibrations measured in the outer part of the ring can be different from the actual vibration patterns. Therefore, the geometric characteristics must be considered for damage analysis. The damage monitoring of direct drive train wind turbines is a new application of CM-systems and it turns out that the current focus of CMS to detect mechanical faults is a limiting factor in this application. Special – rather unconventional – parameters must be monitored in direct drive train setups for a reliable damage monitoring system, e.g. monitoring the generator air gap. Such wind turbine concepts show a higher failure rate of electrical components, therefore the focus on mechanical damages in a direct drive train wind turbine concept must be questioned in general when it comes to monitoring drive train damages with CM-systems.

ISO 13379-1 provides an overview of vibration-based signal processing methods for rotating components.

<u>Time-domain analysis methods</u>

- Statistical- and parameter-based methods

Statistical- and parameter-based data analysis methods principally use minimum and maximum values, peak-to-peak values, root mean square values, or crest factors (relation from peak to RMS-value) for data analysis. Those basic parameter-based evaluations are often fundamental for more advanced analysis methods. Furthermore, simple parameter-based statistical evaluations can be used for a basic trend analysis of the health conditions of a specific component by comparing values from healthy operating conditions with the current operational conditions.

- Time synchronous averaging

Time synchronous averaging is one of the most common data analysis methods for gear CMS (Siegel et al. 2014; Garcia Marquez et al. 2012). The basic technique is to resample vibration data in order to extract periodic waveforms out of vibrational noise to analyze rotating bearings or gearbox defects (Bechhoefer and Kingsley 2009). The technique requires a reference pulse for aligning acquired data to the given shaft. Additionally, phase information is highly necessary for time synchronous averaging. However, bearing damage signatures are usually non-synchronous to the shaft order. Furthermore, planetary gears bear special difficulties, because not all gear meshing frequencies are multiples of the shaft frequency (Luo et al. 2013). Siegel describes a planet separation method for planetary gearboxes using acceleration data as basis (Siegel et al. 2014). In most cases, averaging is carried out from an order analysis as basis. An increased number of averages leads to a better signal to noise ratio (SNR) (Sheng 2012).

- Amplitude demodulation

Demodulation of amplitudes has proven a reliable method for assessing defects from impacts in the gearbox system, such as rolling contacts in bearings or tooth-to-tooth contacts in the gear meshes. It allows the extraction of low amplitudes and frequencies that were not easy to detect because other elements in the vibration spectra have higher vibrational energy. Furthermore, it provides a good visualization of bearing defect frequencies without interference of gear mesh frequencies in the same spectrum. McFadden presents an approach for analyzing vibration data with amplitude demodulation (McFadden 1986).

Frequency domain analysis methods

- Fast Fourier Transform and spectrum analysis

Considering the different geometries and kinematics of the drive train, spectral analysis can deliver an information basis to distinguish between normal frequencies and defect frequencies. Spectrums can also reveal detailed diagnostic information on the location of the defect. This is particularly valuable for a complex rotating system such as the drive train of a wind turbine incorporating several bearings, shafts, and gear wheels.

- Power Spectral Density Analysis

A more advanced derivate is the analysis of the overall spectral energy – so-called RMS value – in the side bands divided by the tooth mesh amplitude. This analysis can be carried out on a power spectral density basis. E.g. the degradation of the gearwheel can be observed as an increase in the energy of the sidebands (Hameed et al. 2009). The National Renewable Energy Laboratory (NREL) conducted a round robin project on gearbox damage analysis methods (Sheng 2012). They also researched on the capability of power spectral density analysis in detecting gearbox damages. Figure 4-24 gives an example extracted from the round robin project.

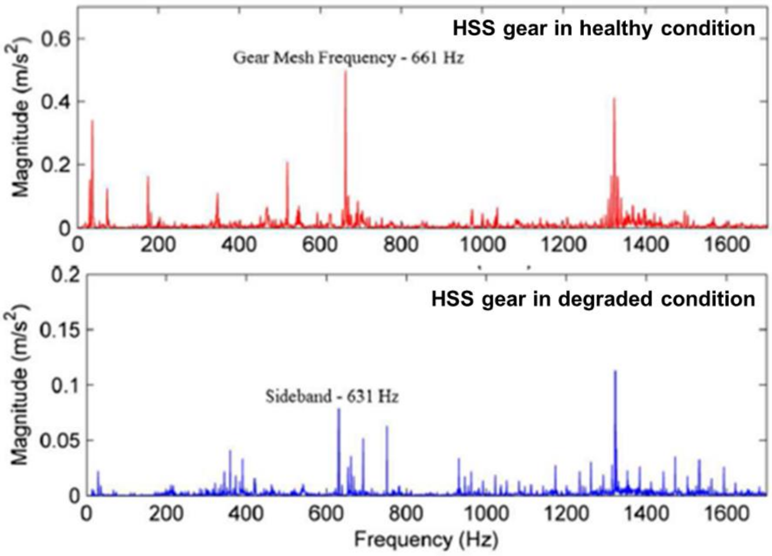


Figure 4-24: Spectral sideband analysis and detection of a degraded HSS gear (Sheng 2012)

- Order analysis

Variable speed wind turbines show a continuously moving frequency spectrum, because of the permanently changing rotational speed. The so-called order analysis is also derived from a basic spectral analysis. The method is based on synchronous samplings. The samples are recorded at equidistant rotation angles but not at equidistant sampling times (Luo et al. 2013). In that way, the smearing of the amplitude energy in the frequency domain can be avoided (Bechhoefer and Kingsley 2009). Order analysis is a useful method for improving efficiency and accuracy in extracting damage features.

- Cepstrum analysis

Cepstrum analysis incorporates the identification of harmonic families from different drive train components in the gearbox. Mathematically, it represents an inverse Fourier transform (FFT) of the logarithmic power spectrum. In application it is a suitable instrument for analyzing series of sidebands that are spaced at a given shaft speed. The so-called cepstrum (reverse for: spectrum) is compared with a healthy baseline condition of the element under analysis. In that way, the condition of each gear wheel can be evaluated. Peaks in the cepstrum are related to a frequency which can identify a damaged shaft. Due to logarithmic values, the cepstrum also takes lower harmonics into account. An exemplary cepstrum analysis was applied in the round robin project of NREL (Sheng 2012), an extract of which is displayed in Figure 4-25.

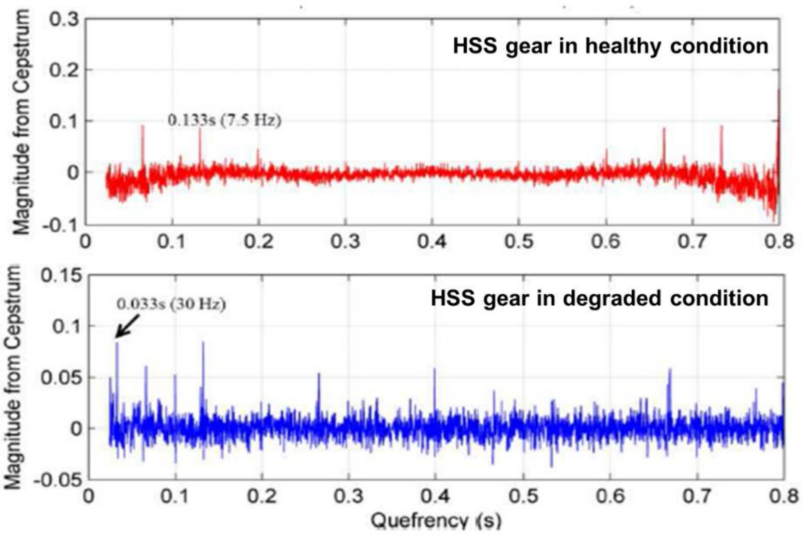


Figure 4-25: Cepstrum analysis and detection of a degraded HSS gear (Sheng 2012)

- Envelope curve analysis

The envelope curve analysis is a process of demodulation of vibration components with a small amplitude in a narrow frequency band, which are often covered by vibration components with higher amplitudes in a wider frequency band. The methodology allows detecting faults with a high certainty according to ISO 133373-1. Most applications are diagnostics of gearboxes and ball or roller bearings. However, in application it is necessary to apply a band-pass filter near the excited natural frequency. After filtering, the Hilbert transform is used to extract the envelope signal, which is then analyzed in detail. If a bearing is damaged on the rolling element, the bearing fault frequency peaks are much easier to distinguish in the envelope spectrum compared with the normal frequency spectrum. Also, the method requires a high sampling rate to capture the excited resonance frequencies, often more than 10 kHz is required. A crucial and challenging element is the selection of the band-pass filter for the center frequency and bandwidth.

- Spectral kurtosis filtering

The filtering method is based on a short-time Fourier transform (STFT) of the vibration signal. The goal is to find an impulse fault signature that is hidden in the raw vibration signal. Impulse signatures can indicate faults in damaged gears or bearings. For this approach several advanced steps are necessary. The signal gained from the filtering process is multiplied by the frequency domain representation of the original signal. The result is then transformed in the original time domain. Siegel applied the method for a degraded gear box (Siegel et al. 2014).

- Wavelet analysis

The wavelet-analysis represents a time-frequency analysis technique, similar to the STFT method described above. However, the wavelet analysis method bears additional advantages for non-stationary signals. The method enables better frequency resolution at low frequencies and better time resolution at higher frequencies compared to the STFT method. Therefore wavelet analysis shows advantages in most practical cases (Watson et al. 2010). Wavelet analysis studies have been applied to fault detection cases in general mechanical applications, not directly linked to a wind turbine application (Wang and McFadden 1996). Changzheng and Zhang evaluated the implementation in order to monitor vibration levels in gearboxes, as well as to identify gear box anomalies (Changzheng et al. 2005; Zhang and Liu 2013). Watson validated the method for a generator damage diagnosis in a test rig (Watson et al. 2010).

If a vibration-based CMS has detected a fault, several proceeding steps must be followed, e.g.:

- The severity level of the detected failure must be defined
- Following maintenance actions must be derived
- Depending on the degradation process, the remaining useful lifetime must be predicted

Jardine conducted a comprehensive review on machinery diagnosis. Different suitable methods for a combined data analysis of event data and CMS data were presented (Jardine et al. 2006). Furthermore the Health and Usage Monitoring Systems (HUMS) and Engine Management System (EMS) in civil and military aerospace systems lead to derived approaches for specific wind turbine applications (Fischer 2012). Generally, severity levels and residual life-time prognosis are often based on expert judgement and experience values. Subjective expert judgements lead to manually set thresholds values and defined following actions. Fully quantitative methods are not applied so far in this context.

CMS analysis needs expert knowledge for data interpretation. Expert recommendations are made in special CMS centers, providing the operator with an interpreted analysis report, indicating possible faulty components with color codes for example. The responsibility considering further maintenance actions based on such reports is with the operator. However, in many cases, the CMS analyst does not receive the information gathered during further inspections of a faulty component from the operator – irrespective if the CMS analysis is done in-house or externally. Therefore, an integration and combination of monitoring data analysis and updated information from inspections on the specific turbine and component is not done so far. Furthermore, the correct configuration and set-up of the CMS parameters is essential for delivering correct and appropriate analysis results. Therefore, a CMS system needs correct information of the exact component set-up and must be informed if any changes are made in the set-up during the lifetime of the specific component.

The fault detection performance of vibration-based CMS varies between failure modes, monitoring system and monitored components. Wirth estimated the detection rate for damages in the high speed stage of a gear box at approximately 96 % (Wirth 2012). Detection rates for low speed components like the rotor main bearing or planet bearings are claimed to be above 80 %. However, some operators claim lower detection rates, especially for planetary gearboxes. Furthermore, the reduction of false alarms is an issue (Fischer 2012; Yang et al. 2014).

4.5.3 OIL-BASED CONDITION MONITORING SYSTEM

Oil condition monitoring is applied in wind turbine gearboxes primarily. The technology pursues basically two different objectives. One the one hand, the properties of oil are monitored to assess the quality of the lubricant oil including the effectiveness of the filter system – therefore assessing the necessity of an oil change. On the other hand, information on wear debris in the lubricant oil can indicate a developing fault in the mechanical system. Considering the set-up of the oil-based CMS, there are both online and offline oil monitoring systems. Offline systems are based on regular oil sampling and a following laboratory analysis. Online systems are integrated in the lubricant systems of the wind turbine gearbox.

Looking at instrumentation and data acquisition, there is a large variety of products in the market. While all systems provide sensors measuring oil pressure, temperature, and particles, there are further parameters indicating oil performance and oil condition in theory. Figure 4-26 displays the basic physical principles of oil-based condition monitoring.

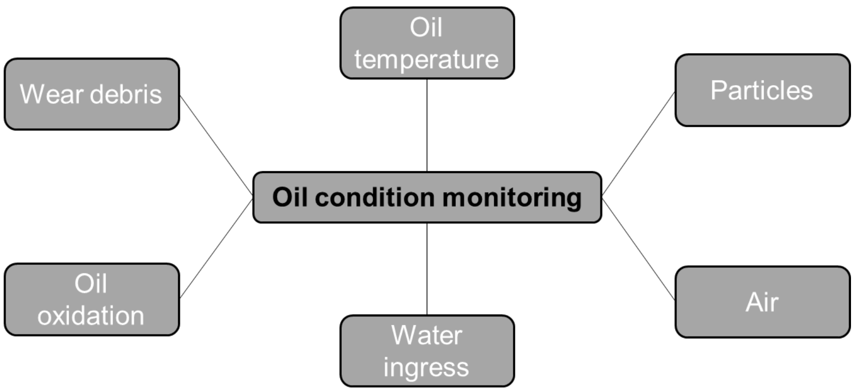


Figure 4-26: Basic physical principle of oil-based condition monitoring

Zhu provides a detailed overview of oil-condition monitoring (OCM) sensors (Zhu et al. 2013). Most commonly, a state of the art OCM systems measures the following parameters:

- Water content
- Particle concentration
- Wear debris production
- Dielectric constant
- Viscosity

Table 4-5 gives an overview of oil-condition monitoring sensors and their specific application and technology readiness level.

Table 4-5: Overview of oil-condition monitoring sensors

Type of sensor	Output signal	TRL and application
Water content sensor	Water saturation [%]	Laboratory tests, validation required
Particle-concentration sensor	Particles size distribution according to ISO 4406	Laboratory tests, prototype tests executed
Wear-debris sensor	Number of particles per unit of time and size	Standard part of CMS of modern wind turbine systems
Dielectric constant sensors	Dielectric constant	Laboratory tests
Viscosity sensors	Kinematic viscosity	Laboratory tests
Oil properties sensor	Viscosity, temperature, density, dielectric constant	Prototype tests
Oil quality sensors	Color-code, quality index	Laboratory tests

- Oil quality

The use of particle counting sensors for an oil quality estimation is already state of the art in most wind turbine gearbox systems.

Water content sensors – humidity sensors - measure the relative humidity or saturation level of oil. Water can have several effects on the lubricant oil and can already reduce the bearing life considerably with small concentration levels. The lubricant capacity of oil is affected by water catalyzing oxidation and accelerating corrosion processes of ferrous materials. Moreover, water causes additives to precipitate and fosters the growth of microorganisms. The capacitance measurement is widely used as physical principal for a humidity sensor. The measured capacitance responds to changes in the relative humidity which can be correlated to the saturation level of the lubricant oil. However, the saturation level cannot directly be correlated to the water content in the system, because the parameters of oil pressure and oil temperature must also be considered.

Particle concentration sensors quantify the number of particles in the lubricant oil based on ISO 4406. ISO defines a cleanliness level in three stages:

a) Concentration of particles $\geq 4\ \mu m$ in 1 ml of fluid
b) Concentration of particles $\geq 6\ \mu m$ 1 ml of fluid
c) Concentration of particles $\geq 14\ \mu m$ 1 ml of fluid

Studies have already shown that the concentration of particles reduces the lubrication performance considerably (Ukonsaari and Moller 2012; Toms 2014). The larger the number of particles, the higher the surface tension of the fluid on the surface of the bearings, thereby leading to a decrease of the effective lubrication film thickness. This circumstance can lead to a significant service life reduction of the bearings. Small particles can also form slit and cause erosion wear. Particle concentration sensors are normally installed in parallel to the lubrication circuit.

Wear debris sensors can identify important and typical bearing damages such as pitting. The sensors detect particles > 50 µm. However, the flow rate of the lubricant limits the detection capabilities (Toms 2014).

Dielectric constant sensors are based on the physical principle of oxidation in degraded oil. If the oxidation process evolves, the number of polarized molecules increases, changing the dielectric constant of the lubricant oil. The dielectric constant is also known as relative permittivity. The value of the dielectric constant varies with the frequency of the applied electric field. It is not possible to measure the dielectric constant directly. Experimental results in Yu-mei et al. (2009) revealed correlations between the moisture content, acid number and iron content with the dielectric constant of the lubricant oil.

Viscosity sensors measure one of the most important parameters of a lubricant. Viscosity is generally defined as the flow internal resistance of the fluid. The viscosity of the lubricant oil is directly connected to the lubrication film thickness. Viscosity measurements need the fluid to be sheared. The performance of the sensor depends on the measurement principle and the environmental conditions. One way of measuring is using acoustic signals. A change in viscosity can be caused by several combined aspects, thus making it difficult to use viscosity changes for an exact damage detection in the drive train system. However, general degradation can be detected by changes in the lubricant oil viscosity (Ash et al. 2003).

So-called oil quality or oil property sensors represent combined sensors based on the measuring principles described above. Evaluations take place by color code or quality indices, indicating the oil condition. Most of the combined sensors integrate measurement of dielectric constant, temperature, and viscosity values. Considering practical applications, a drawback is the missing standard procedure for choosing correct threshold values for failure detection. The correlation of the measured values and interpretation for the wearing status of the drive train components is still under ongoing research.

The data processing and diagnosis methods for OCM systems are rather straight-forward compared to the data analysis methods for vibration-based CMS data. In an OCM analysis a classical trend analysis is typically used to analyze the measure parameters over time.

For offline monitoring particle counts it must be said that taking the sample after a longer stand still period will most probably lead to higher particle counts then after several hours of operation. However, the wearing condition might be the same.

Another important aspect – for on- and offline systems – is the placement of the sensors or sample taking considering the oil filter system design in the lubrication system. Figure 4-27 displays a generic wind turbine drive train lubricant system and its filter systems.

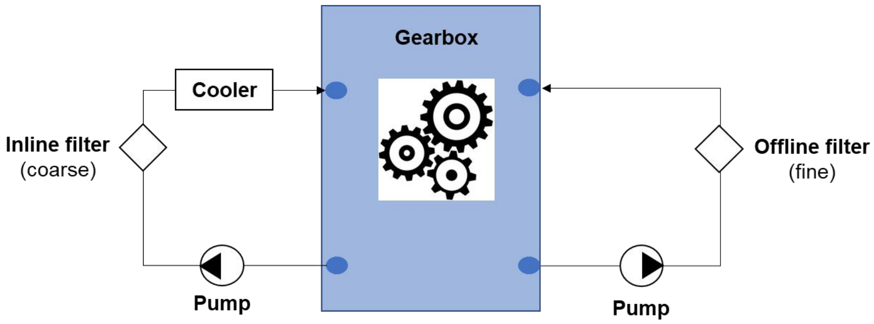


Figure 4-27: Filter configuration in a generic wind turbine lubricant system

The residual lifetime prognosis based on OCM data is still at an early stage. One approach is shown in (Zhu et al. 2014). Based on viscosity measurements and dielectric constant sensors, Zhu developed a model for correlating between oil degradation and the oil particle counting system. The approach is validated by laboratory tests. However, the utilization of OCM systems plays a key role in wind turbine O&M management. A next innovative step would be to combine oil-based measurement with vibration measurement to a holistic on-line condition monitoring system for wind turbine gear boxes.

4.5.4 VIBRATION-BASED STRUCTURAL HEALTH MONITORING

SHM methods for wind turbines are still in a development phase. The standard procedure of monitoring an important structural element of a wind turbine – e.g. a rotor blade – is still performing visible inspection by expert blade and service engineers, especially for safety-related shut downs of the turbine system and maintenance tasks. Available SHM systems show lacking safety and reliability which must be addressed in future.

Acceleration measurements are always absolute measurements, with no need of data comparison. The mathematical background of acceleration-based measurements is the second law of Newton. This physical principle is based on the time variation of the impulse of a body, the sum of acting forces on a body. If the acceleration of a body is measured, the time wise integration leads to the speed of the body.

$$\vec{v}(t) = \int_0^t \vec{a}(t)dt + \vec{v_0}$$

Equation 4-10

The next step of integration over time, leads to the displacement of the body.

$$\vec{s}(t) = \int_0^t \vec{v}(t)dt + \vec{v_0} \cdot t + \vec{s_0} = \iint_0^t \vec{a}(t)dt + \vec{v_0} \cdot t + \vec{s_0}$$

Equation 4-11

In theory the calculation is relatively easy, assuming speed and location of the body are known. In practical applications, offset failures can corrupt the data – especially when dealing with low frequent or constant effects. A practical approach of wind turbine acceleration measurements was developed during the *MISTRALWIND* project (Geiss et al. 2017).

Applied sensor types in structural health monitoring systems are:

- Accelerometers
- Piezo-electric sensors
- Micro-electromechanical systems (MEMS)

Frequency domain analysis methods

- Operational Modal Analysis

One of the most common forms of vibration-based SHM methods is the operational modal analysis (OMA). Changes in the geometric or stiffness properties of the structural element will lead to changes in the natural frequencies of the structural element. The vibration spectrum of a rotor blade inherits a variety of independent natural frequencies per direction of movement, forming an individual vibrational identity of the structural element. However, the vibrational spectrum is not only dependent on the structural integrity, it is also influenced by wind excitations. Intrinsic faults of the rotor blades – like flaws in lamination or balsa wood parts and bonding issues – will not be detected (Rolfes et al. 2014).

Natural frequency tracking is not very sensitive to structural damage. A change in eigenfrequency can reliably be detected for changes over 0,2 %. Assuming a standard-size rotor blade, this leads to a minimum detectable crack size of 140 mm (Benedetti et al. 2011). The analysis of mode shape changes shows to be more sensitive to local damage than the described eigenfrequency analysis. However, mode shape analysis can be influenced by unknown ambient loads and inconsistent sensor positioning.

In addition, during the above described wavelet analysis, information may be received of damage from non-stationary components of the vibration signal.

4.5.5 STRAIN-BASED STRUCTURAL HEALTH MONITORING

Direct mechanical strain measurements in wind turbine application is usually performed using two different types of sensors: strain gauges or optical fibers. However direct strain measurements for other industrial or research applications can be performed by a variety of other sensor concepts and techniques – e.g. micromagnetic analysis in the automotive industry.

Strain gauges

When an electrical conductor is stretched its electrical resistance increases. The conductor is bonded to the relevant surface; strain of the structural surface will be reflected in change of the resistance. A practical disadvantage of strain gauges is drift of the sensor data. One common reason are environmental temperature influences.

Optical fibers

In comparison to electric strain gauges, optical fibers have advantages in lightning safety and robustness against electro-magnetic interference, because the light source is insensitive to electromagnetic fields and the glass fiber is not electrically conductive. The main advantage of optical fibers is the amount of structural information in relation to the installation complexity compared to electrical strain gauge installations. Long transmission paths of several hundred meters can be realized without the need to install measuring amplifiers. Furthermore they show a higher resistance to disbanding, creep, and fatigue in an operational environment (Hameed et al. 2009). A major disadvantage is the complex sensor coupling to receive accurate data. This holds especially for in-situ applications in which the constructive concept is decisive for prosperous measurement results in operation. Fiber optical strain gauges make use of the physical relation between the measured Bragg wave length and the structural strain. However, due to the physical concept, FBGs require temperature compensation. Generally, optical fibers consist of two components: a core with a diameter d_{Core} and refractive index n_{Core}, and a cladding with a diameter $d_{Cladding}$ and refractive index $n_{Cladding}$. Cladding and core are made from high transparent glass. The refractive index of the core is higher than the refractive index of the cladding. A coating protects the fiber from environmental conditions and mechanical loads. Figure 4-28 displays the generic structure of a fiber optical sensor.

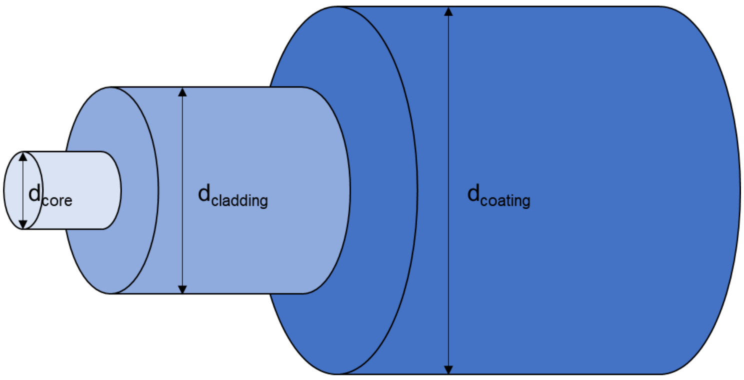


Figure 4-28: Generic structure of a fiber optical sensor

The diameter of the core is between several micrometers and several hundred micrometers. There are monomodal and multimodal fibers. On the boundary layer between core and cladding, a light beam travels through the fiber with $n_{Core} > n_{Cladding}$, with the angle γ. The light beam is partly reflected and partly refractioned, with the refraction angle ε.

Total reflection is determined as:

$$\gamma_{max} = \cos^{-1}\left(\frac{n_{Cladding}}{n_{Core}}\right)$$

Equation 4-12

Fiber-Bragg-Gratings (FBGs) use the periodic modulation of the refraction index in the core. They inherit a filter which reflects light with a Bragg-Wave-Length λ_B and transmits the light beam out of the wave length area. Figure 4-29 displays the operating principle graphically.

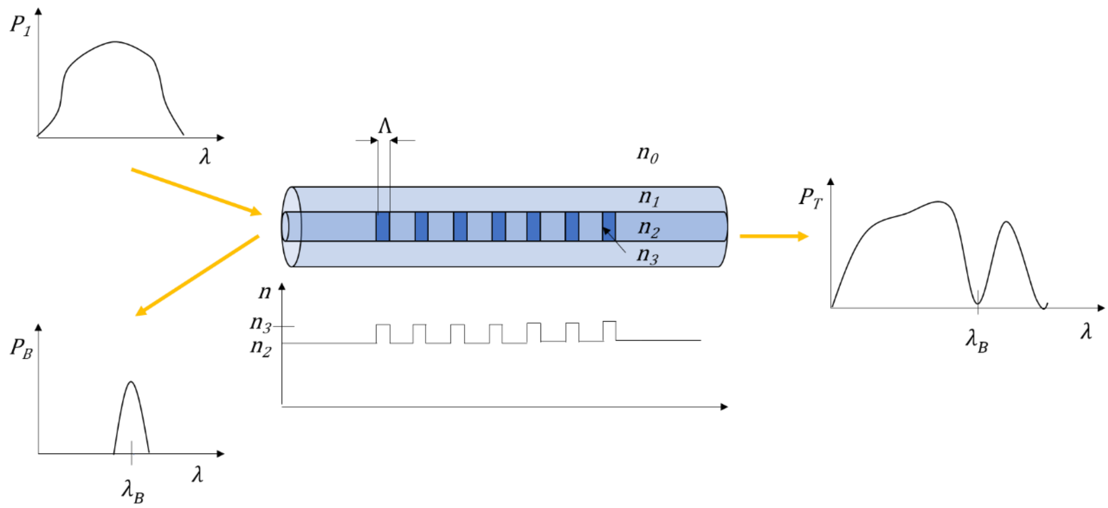


Figure 4-29: Operating principle of FBGs

The Bragg-Wave-Length λ_B is defined by the length of the period of the refraction index modulation Λ:

$$\lambda_B = 2 \cdot n_{eff} \cdot \Lambda$$

Equation 4-13:

The refraction index and refraction index modulation vary because of temperature differences and mechanical strain. Strain related wave length alternation is defined by geometric variation of Λ and variation of the refraction index of the glass material because of the elasto-optic effect.

Signal evaluation is performed with spectrometers from optical information to electrical information. Strain-based SHM is predominantly applied for load monitoring. However, it is also suitable for damage detection. A high number of sensors is necessary for detecting small damages – especially when applying electrical strain gauges (Rolfes et al. 2014). In combination with a suitable fatigue model, strain measurements are fundamental for a residual lifetime analysis (Lachmann 2014).

4.5.6 DEFLECTION-BASED STRUCTURAL HEALTH MONITORING

Deflection-based structural health monitoring can be based on various monitoring techniques. Currently most common are laser-based systems which are used for various structural parts of a wind turbine system thus guarantying good accessibility. Most laser-based systems are currently applied for rotor blade monitoring. Laser-based systems measure deflection at the tip of each blade. When the blade crosses the laser beam, the deflection data is correlated with operational data – e.g. wind speed, pitch angle, rotor speed. The deflection information can be utilized to provide information on the structural status of the blade, e.g. the bending stiffness of the blade. Structural parameters like the bending stiffness, can be related historically or in relation to the other two blades of the rotor system. Also, the detection of icing or the detection of a pitch error of one of the blades is possible (Rolfes et al. 2013). Other monitoring techniques for deflection monitoring of wind turbine structures under development are photogrammetricbased measurements (Botz et al. 2017a), radar beam interferometry and the application of Global Navigation Satellite Systems (GNSS).

Especially GNSS deployments experienced advances in the last years concerning accuracy and availability. Currently, three national or regional navigational satellite system are available. The American GPS system is the oldest, most established and developed system and has been operative since the 1970s. The European Galileo-System is advancing and could prove promising in the upcoming years. Available is also the Russian GLONASS-system. Several studies have proven that a practical accuracy in a wind turbine monitoring use case is down to several centimeters using standard GPS-antennas, Real-Time-Kinematic GPS antennas respectively (RTK-GPS). Gruber conducted more sophisticated studies for wind turbine use cases (Gruber 2018). Feilen and Geiss worked on mm-wave based deflection measurements (Feilen et al. 2017).

4.5.7 ACOUSTIC EMISSION TESTING

The acoustic emission analysis technique is comparable to seismological applications and is categorized as a so-called passive NDT method. The testing principle is focused on the detection of acoustic waves, emitted by fractures. Strain or damage within or on the surface of a solid material releases high frequency transient elastic waves in the material (Mba and Rao 2006). Mostly piezoelectric sensors are applied and mounted on the surface of the specimen for detection of acoustic waves and localization of the emission source (Grosse and Ohtsu 2008; Grosse 1996). The signals can be characterized in terms of amplitude and energy. The frequency range of acoustic emission waves is typically between 20 kHz and 1 MHz (Molina 2010). Monitored conditions are the plastic deformation or the crack formation caused by loading of the specimen, by recording elastic waves during the structural deformation of the loaded structures. In this manner microscopic deformations in the structure are detectable. Failures or discontinuous areas in the specimen, which the specimen already inherited before the installation of the measurement system are not detectable if they do not emit waves during loading. However, due to an early detection capability of the method, the detection of fatigue failures may be possible before the actual fatigue damage of the structure occurs. The evolving failure “produces” a characteristic sound pattern, which is analyzed. The interpretation of data is only possible if the source of the sound within the specimen is detected and localized. A measurement set-up is possible with single sensors or sensor arrays. Figure 4-30 shows the basic principle of acoustic emission monitoring.

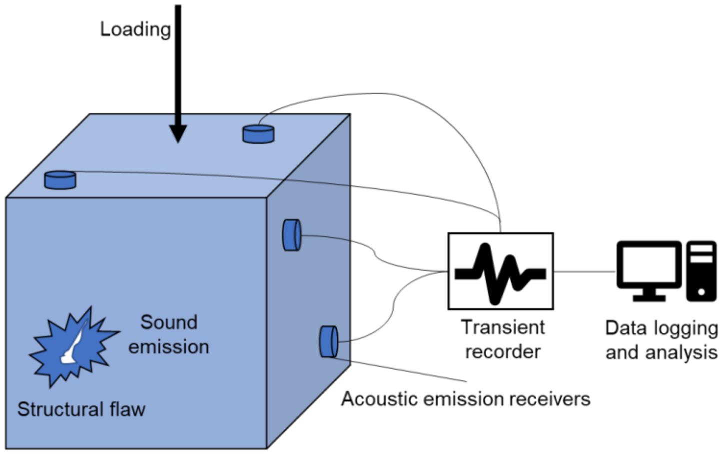


Figure 4-30: Basic principle of passive acoustic emission monitoring – adapted from (Grosse 1996)

Acoustic emission analysis can be subdivided in two main data analysis methods: parameter-based and signal-based acoustic emission analysis. Both methods focus on the analysis of failures in space and time. The parameter-based analysis aims at the extraction of parameters which are relevant for the failure mechanism, discarding the full length of the data signals. The signal-based analysis records the complete sound signals and is thus demanding in terms of complex data analysis. Localizing the signal sources is fundamental. This incorporates knowledge of the damage course, mechanisms of fracture mechanics, and distinguishing failure signals from noise. Specific localization algorithms are designed on single applications and are not generally interchangeable. For a three-dimensional detection of the signal source – the so-called hypo center – in a structural body, one needs the minimum information of four arrival times from compression waves (p-waves) or shear waves (s-waves) in more than two sensor locations. For a plate-shaped structure, the application of lamb waves is possible (Berger and Hayo 2014). All measurement results produced in operation of the structure are not reproducible.

Acoustic emission testing can be applied for damage detection of rotor blades. Therefore, piezoelectric sensors are applied on the rotor blade structure to detect high frequency structure-borne elastic waves, which are initiated by structural damages such as cracking or debonding. However, in order to detect small damages as well as localize faults in large structures, a high number of distributed sensors is necessary (Rolfes et al. 2014).

Practical applications in operating environments outside of the laboratory bare difficulties due to noise from other sound emissions, leading to a reduced quality of the output signal (Ahmad and Kamaruddin 2012). However some successful implementations exist in monitoring of bearings and gearboxes (Molina 2010; Sheng et al. 2010) and damage detection on wind turbine rotor blades (Wei and McCarty 1993; Frankenstein et al. 2008; Frankenstein et al.; Schubert et al.).

4.5.8 ULTRASONIC TESTING

The basic principle of all known variations of ultrasonic testing methods is based on the relationship between frequency and amplitude of the ultrasonic signal. Compared to the acoustic emission analysis, the ultrasound-based testing method is more dependent on the geometrical properties of the specimen. An ultrasonic impulse is sent into the specimen and recorded in transmission. For a classical run-time-analysis one needs a sufficient determination of the distance between transmitter and receiver. The run-time of the direct wave is measured. Normally the direct wave is a compression or shear wave. The compressional wave is the fastest wave within the specimen, also known as the primary wave. The evaluation can be corrupted in practice by falsely detecting wave forms other than the primary wave, e.g. s-waves or surfaces waves with a higher amplitude than the primary wave. The accuracy of the run-time measurement is dependent on the resolution performance of the measurement device. Another practical issue is the coupling of transmitter and receiver on the specimen. Several coupling mediums are practically applicable, such as wax, silicon, plaster, plasticine, oil and water. Which coupling medium works best is heavily dependent on the surface composition of the specimen (Jüngert et al. 2009; Jüngert et al. 2008; Große 2012; Geiss and Hornfeck 2015).

Another basic method is the amplitude evaluation of the transmitted signal. Deteriorations within a specimen leads to an amplitude reduction because of reflection effects within the signal's pathway in the material. For a high significance of the measurement results, one often tests the specimens along a line or a profile, or on a pre-defined surface – a so-called scan. The comparison of measurement parameters is easier in scan mode.

Theoretically there are three or four different categories of ultrasonic scans:

- A-Scan
  - Registry of amplitude over time at a single point
- B-Scan
  - Measurement along a profile with and individual pre-defined measurement points
- C-Scan
  - Measurement of several parallel B-Scans
- D-Scan
  - Evaluation of C-Scan along depth profile

A modern variation of the classic testing method is represented by the impulse echo method, which shows advantages when the specimen is only accessible from one side. The measured impulses are the signal's reflections from the backwall of the specimen – the so-called backwall echo. Therefore, transmitter and receiver are on the same side of the specimen. If the specimen inherits a defect, an additional echo is visible. Through the time difference between the sending impulse and the backwall echo, one can determine the depth of the defect. An important boundary condition for this testing mode is that the sending impulse must be short enough for the sending impulse to fade away before the backwall echo reaches the receiver. Thus, there is a minimum time interval correlating with a minimum material depth in which failures can be detected. Too much reflection in inhomogeneous materials make analysis difficult. Figure 4-31 displays the basic measurement principle of ultrasound impulse echo testing.

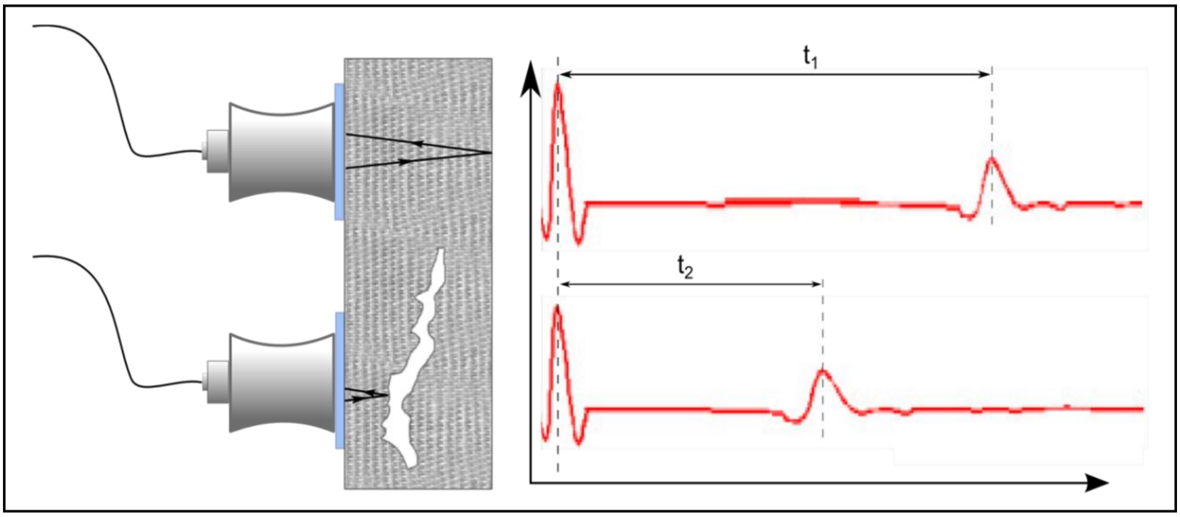


Figure 4-31: Basic principle of ultrasound impulse echo testing (Hornfeck et al. 2015)

An immense number of literature is available on ultrasonic material testing, a summary is provided by Workman and Moore (2012). Application examples for wind turbine testing are given in Rolfes et al. (2014). How nondestructive testing techniques can be integrated into a holistic asset management system will be shown in chapter 4.6.3 and the following.

Among data analysis concepts for detecting damage evolution processes, active and passive interferometric methods – like the coda wave interferometry – promise best results using ultrasonic data. The name coda wave is deducted from Latin, in which coda is synonymous for "tail". Seismology uses coda wave analysis to describe the ending of a seismogram. The final part of a seismogram is often a mixture of all types of waves. The coda wave interferometry uses a cross-correlation of a stretched portion of a measurement and a reference to quantify the average velocity change. Core advantage of applying coda wave interferometry analysis is that large volumes of a structural element can be monitored applying only a small number of transceivers. Furthermore, the techniques are sensitive to early stage damages. However, research lacks so far of completely implemented set-ups of coda wave interferometry in a practical environment using embedded or externally applied ultrasonic sensors to localize defects. Successful applications will have to tackle various influencing environmental factors in field, such as temperature, moisture, stress, and deterioration (Larose et al. 2015; Niederleithinger et al. 2015; Niederleithinger et al. 2014; Planès and Larose 2013).

Figure 4-32 shows the recommended allocation of relevant asset management key performance indicators for the MISTRALWIND test turbine on a sub-system level. Which monitoring technique will be applied to analyze the KPIs is mainly cost-driven and can be evaluated individually in the framework of the holistic damage detection database framework.

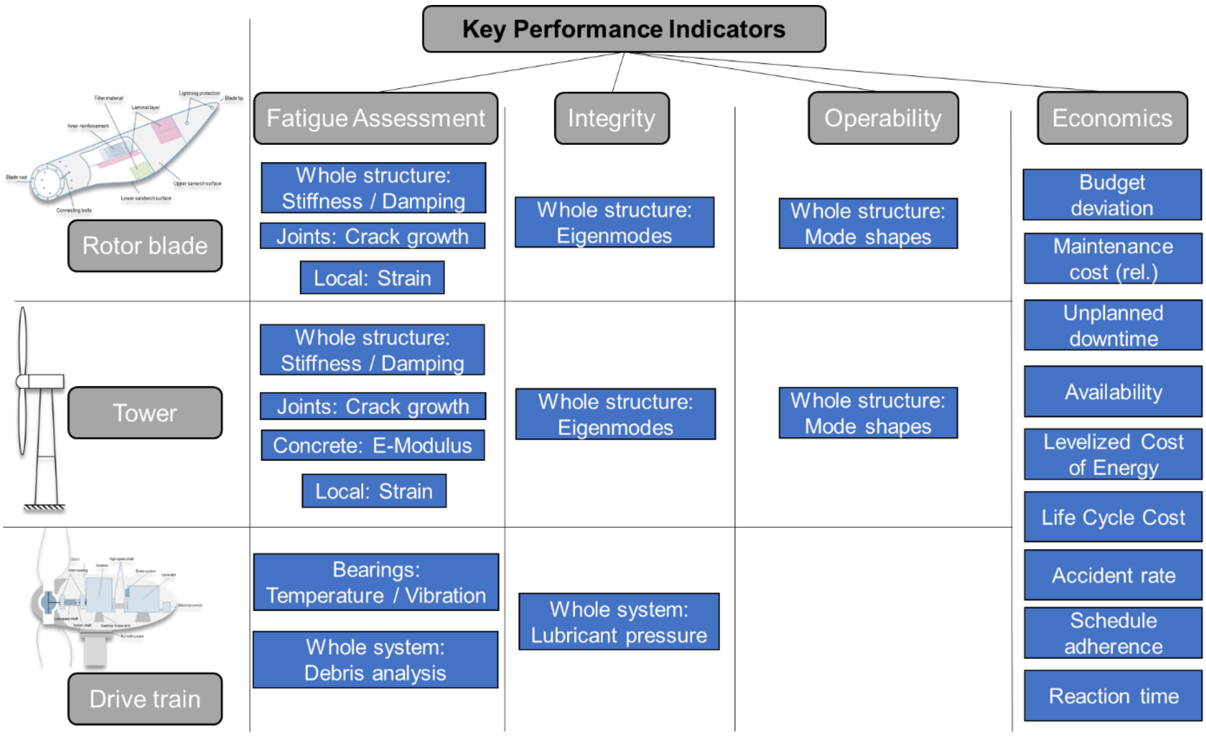


Figure 4-32: Allocation of asset management key performance indicators for MISTRALWIND turbine

4.6 MULTI-LEVEL CONDITION AND STRUCTURAL HEALTH MONITORING

The technological core part of the IAMS-Wind concept is based on a multilevel condition and structural health monitoring concept. Which can be seen as a new and holistic approach to life cycle management for wind turbines. The approach is in no need of complicated and computationally intensive aeroelastic simulation models. The concept combines monitoring and inspection data holistically. Thus, the condition assessment can be done based on the real component loading and is not solely dependent on load simulations and model site parameters, which can bear huge uncertainties. The upcoming paragraphs will lead through the approach. In Figure 4-33 a general graphical overview is given for the multilevel condition and structural health monitoring concept.

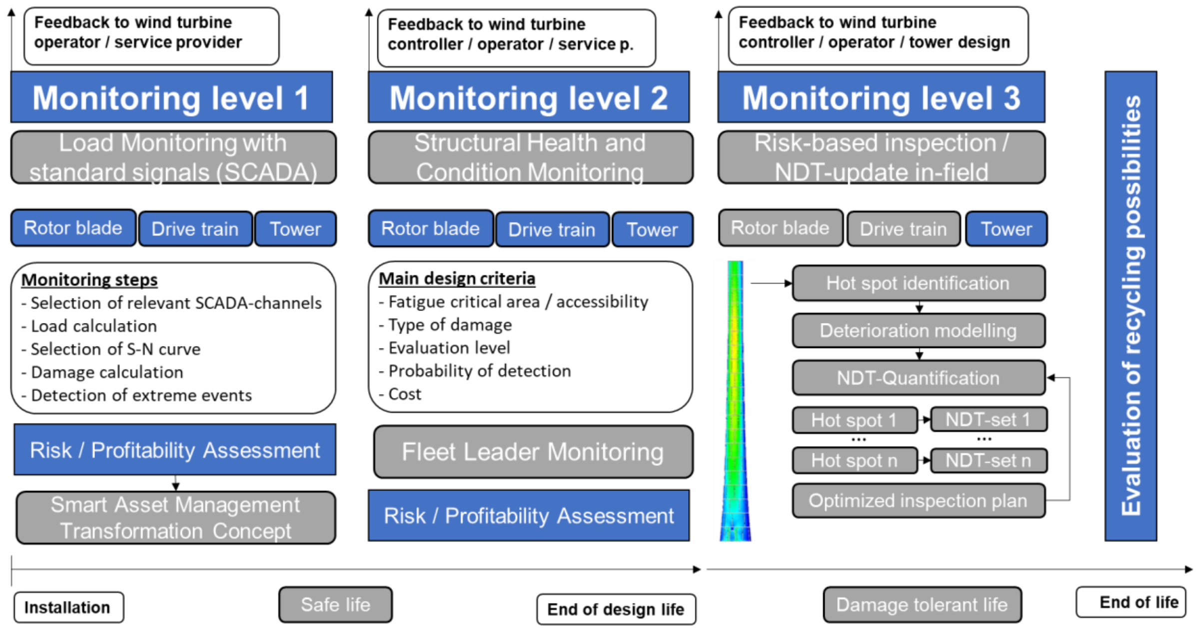


Figure 4-33: Holistic multi-level condition and structural health monitoring concept

The approach consists of three monitoring levels, for which the monitoring scope but also the cost and effort increase from one level to the next. Monitoring level 1 is concerned with load monitoring using standard operating signals from the wind turbine's SCADA system. Chapter 4.6.1 will introduce a methodology which in three basic modules for rotor blade, drive train, and supporting structure system enables operators to conduct a fast fatigue check to analyze the past consumed service life of the main components on a load monitoring basis. However, the data resolution is not highly sophisticated in monitoring level 1. SCADA data channels sample with a frequency of 0.001 Hz. In some cases, it might be possible to access a deeper level of the SCADA-data system, for which the sampling frequency is 0.2 … 2 Hz and is mainly used for the wind turbine controller. For older turbines, SCADA-load monitoring in level 1 might be the only economically possible option to conduct condition or structural health monitoring. For most wind turbines, however, monitoring level 1 will not be accurate enough to predict a possible remaining useful service life (RUL), and detect and predict damages in the system. Therefore, monitoring level 1 is consecutively combined with monitoring level 2 for structural health and condition monitoring with separate sensor system and monitoring level 3 for updating monitoring data with nondestructive testing results from damage hot spots in the field. The claim to design a holistic monitoring and inspection approach implies the combination of monitoring data and inspection data. The few already existing approaches for wind turbine condition and structural health monitoring mainly focus on monitoring (Kamieth et al.; Lachmann 2014). However, in practice it cannot be assured that the chosen sensor position for the additionally installed monitoring system is also the relevant hot spot which will fail in the system. Therefore, condition and structural health monitoring can only be considered holistic if it combines indirect load monitoring, standard signals, and separately installed system and in-field inspections. The choice of monitoring level is mainly driven by the optimal relationship between monitoring effort and cost, and the resulting cost benefits or safety reduction benefits for the operator. This decision can be supported by a risk and profitability analysis as conducted in chapter 4.3. Furthermore, the installation of a sensor and monitoring system should be conducted in a defined transformation process, which will be handled in chapter 5.3.2. However, in practice, such a quantifying analysis can also lead to the conclusion that any monitoring or inspection effort might not overrule safety or profitability issues. The logical conclusion of such outcomes in a life-cycle-based asset analysis, is to analyze recycling and decommissioning possibilities for the wind turbine system. Figure 4-34 displays the described optimization problem, which will need to be considered in detail before more sophisticated monitoring and inspection efforts are performed. As the cost for monitoring, inspection, and sensor systems decreased rapidly in the last decades, it has proven beneficial to "buy" additional information with monitoring and inspection techniques and use this information to optimize the operation and maintenance activities of wind turbine systems on micro and macro economical scales. In addition, the wind industry in Germany is currently experiencing a recession due to the decreasing feed-in tariffs and the increasing complexity and difficulty to install new wind turbine projects. Applying cost-optimal monitoring and inspection systems can also be a catalyzer for the bogging wind turbine industry in Germany and Europe and might contribute to reducing the concerns expressed by the public by providing sober facts.

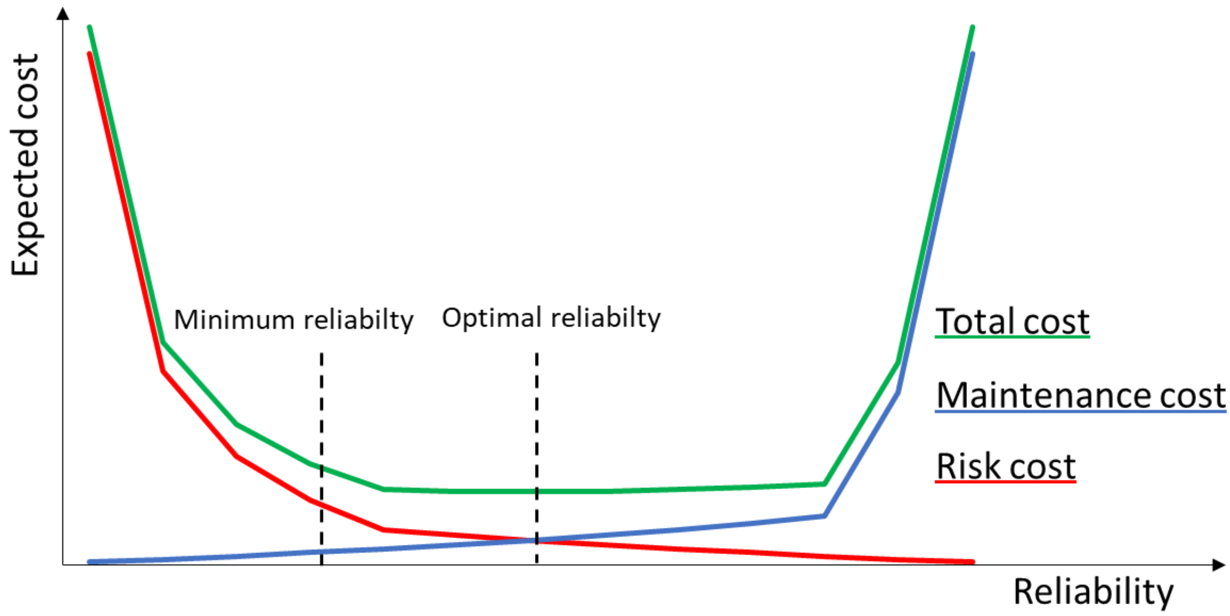


Figure 4-34: Basic maintenance decision problem for monitoring and inspection effort – adapted from (Nicholas and Young 2008)

During the *MISTRALWIND*-research project, monitoring system design on level 2 was mainly conducted by Botz, Raith and Wondra (Geiss et al. 2017). Furthermore, the monitoring activities were focused on the wind turbine tower structure. In a surrounding research project named OCM – On-Condition Monitoring, the author conducted additional research in temperature condition monitoring of main bearings in a wind turbine drive train at IABG laboratories (Geiss 2013). Figure 4-35 depicts the monitoring approach of level 2 graphically.

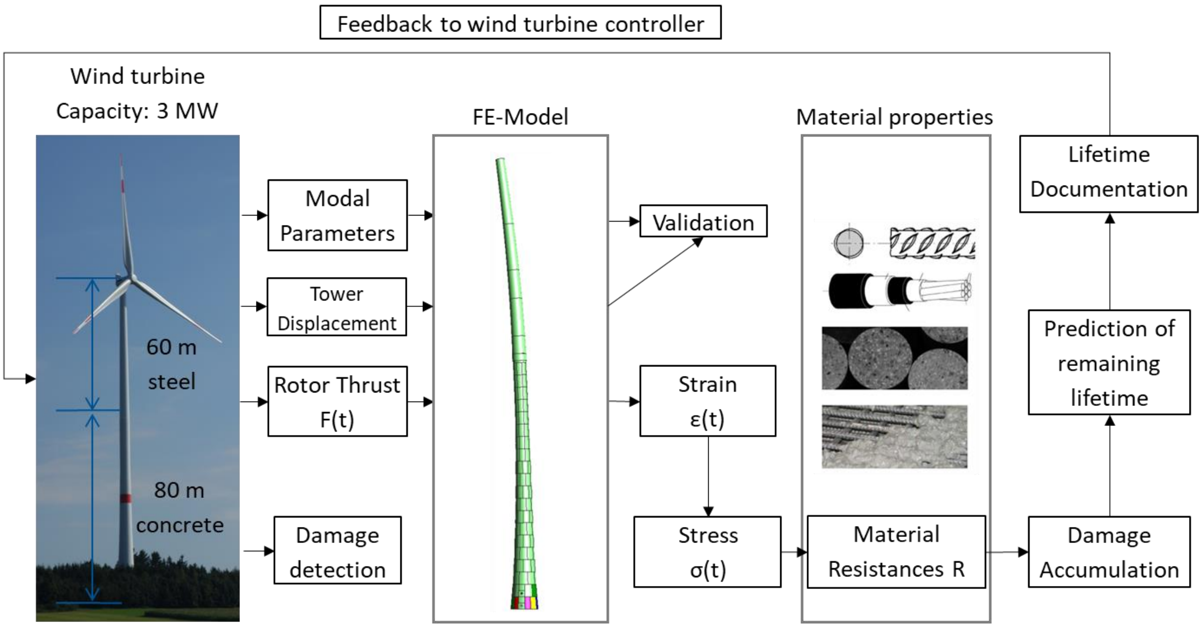


Figure 4-35: Monitoring procedure of monitoring level 2 – structural health and condition monitoring (Botz and Grosse 2018)

The wind turbine's hybrid tower structure was equipped with strain and acceleration sensors on three different levels, ground floor, middle maintenance platform, and nacelle platform level. Additionally, the fundament of the wind turbine was equipped with a stationary seismometer to track its displacement. In a second sensor installation campaign the tower was additionally equipped with fiber optical sensor systems for strain measurements. The structural health monitoring system mainly tracked the tower displacements and the system's modal parameters for damage detection. Figure 4-36 displays the modal parameters of the tower structure in normal operation, which was used as "finger print" of the healthy structural system.

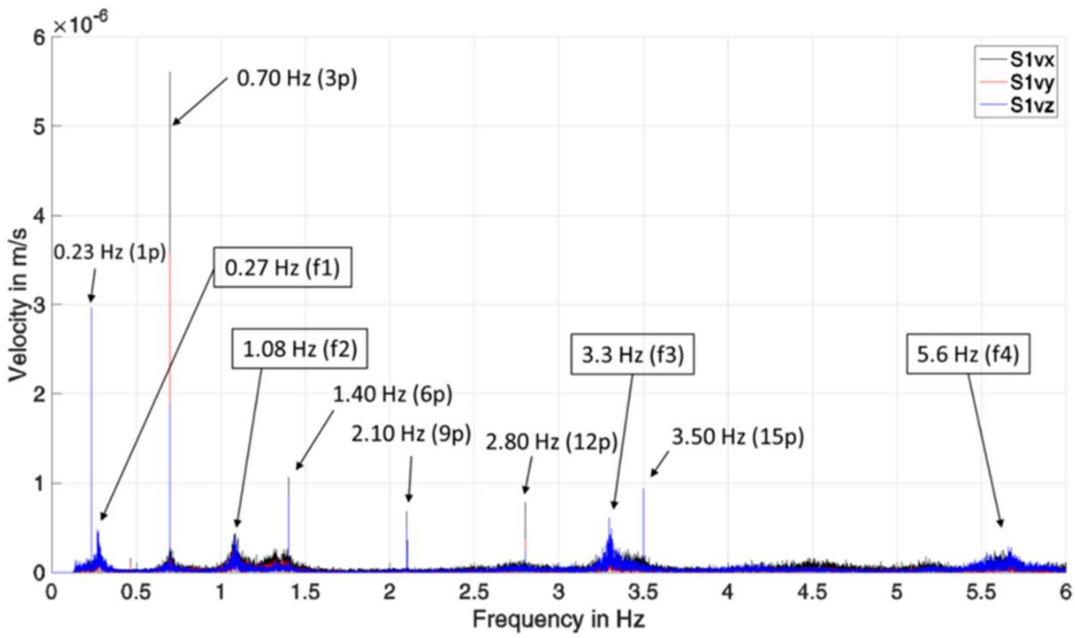


Figure 4-36: Modal parameters of the MISTRALWIND test wind turbine in normal power production (Botz et al. 2016)

The high-resolution tower displacement data was transferred onto the validated FE-model to analyze the stress and strain on all relevant cross-sectional areas of the wind turbine tower structure. Subsequently, the material resistance database developed by the Chair of Materials Science and Testing at the Technical University Munich was used to predict the remaining useful service life of the wind turbine tower structure by considering the application of a *Rainflow* counting algorithm and the provision of linear damage accumulation. Figure 4-37 displays the material strength approach graphically (Osterminski 2016). The resulting RUL prediction was performed periodically and stored in a lifetime documentation for the wind turbine tower structure. Chapter 4.7 will discuss the design and implementation of an integrated asset management database for wind turbine system in detail. Lastly, a reduced FE-model was designed to feed the monitoring information generated in this level 2 back into the wind turbine controller. Obradovic and Wever worked on the optimal controller balance between power output and damage accumulation of the overall wind turbine system (Geiss et al. 2017).

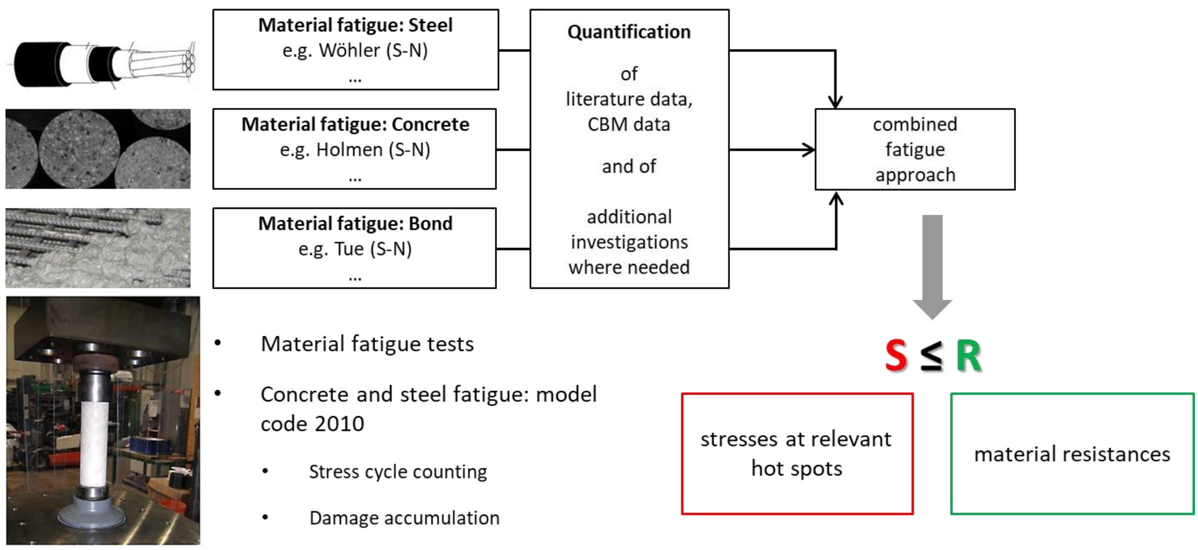


Figure 4-37: Hybrid material strength approach for prediction of RUL on hybrid wind tower structures (Osterminski 2016)

Generally, wind turbine hybrid towers are designed to be “maintenance-free”. Therefore, monitoring level 3 assumes a safe life of the tower structure during the originally designed service life of 20 years. After that, wind turbine towers can enter a prolonged service lifetime phase, which can be described as damage tolerant life of the tower structures. The according authority regulations and assessments were described in chapter 2.4.3. Figure 4-38 depicts the concept of safe and damage tolerant life graphically. Monitoring level 3 seeks to combine monitoring information, which is mainly based on fatigue design laws, with actual in-field information retrieved with nondestructive testing techniques to update the actual remaining useful service life resources. Aiming on this goal the concept of risk-based inspection planning, combining the assumptions of structural reliability analysis and Bayesian updating promises to provide the appropriate instruments and tools therefore. Currently it is unclear how long a remaining useful service life can be in the damage tolerant mode beyond 20 years, because no empirical data exists so far. Loraux worked on service life predictions of wind turbine tower structures and concluded that the remaining service life can be well beyond double the originally designed service life. It is conceivable to reinforce existing tower structures with new construction technologies, e.g. applying UHPC materials as external reinforcement systems, to ensure an adequate safety and reliability level of the structures and to refit towers (Loraux 2017). Assuming this perspective, all main components of a wind turbine system are replaceable units in a life-cycle asset perspective, except for the tower. Optimally timed replacements of main components (rotor blades, drive train components) and wearing components (bearings, clutches, breaking system) should ensure an economic and reliable operation of the overall system, while wind turbine towers remain the main load bearing frame for the overall system or furthermore bear the possibility to increase hub-heights for better wind harvesting conditions. Such concepts are promising to be more economical and sustainable, the analysis of such will be discussed in chapter 5.2. The passages in chapter 4.6.3 and the following will mainly focus on introducing the concept of risk-based inspection techniques for monitoring level 3.

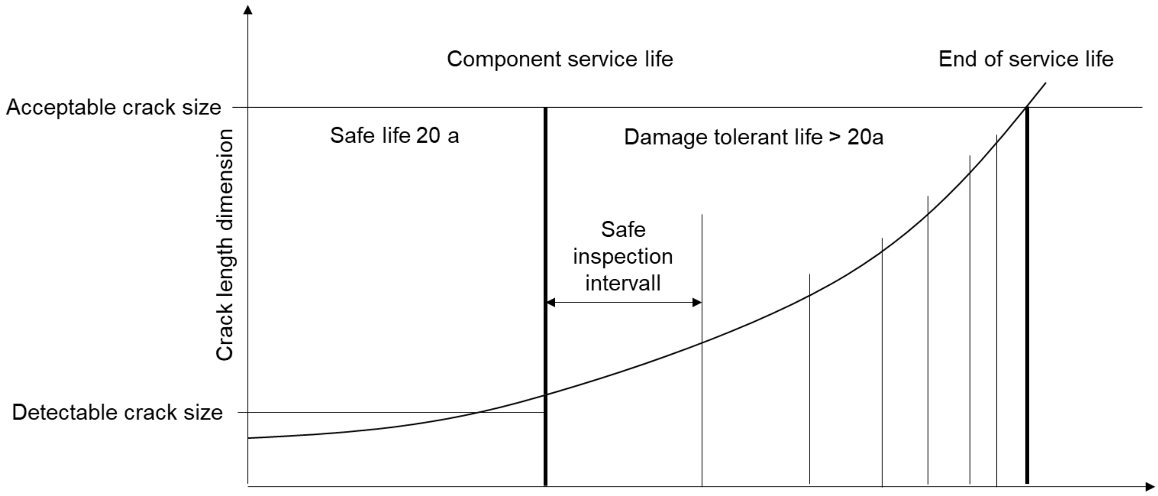


Figure 4-38: Concept of safe and damage tolerant life for wind turbine tower structures

4.6.1 FAST FATIGUE ANALYSIS WITH STANDARD SIGNALS

In order to answer research question **RQ 7**, the following section displays the findings:

Is it possible to establish relations between SCADA-data and load measurements for wind turbine fatigue monitoring?

Load monitoring of wind turbines with SCADA-signals is barely performed in wind energy engineering. Two of the rare examples are the studies of Loraux (2017) and Cosack (2010). Both analyzed internal forces; the laws of stress concentration, crack propagation, and fracture mechanics were excluded. A few successful examples of load monitoring with standard signals are known from other mature asset management industries such as aerospace, military, and nuclear industry (Polanco 1999).

In theory, there are various suitable analysis techniques for the set-up of a load monitoring fed with SCADA-data signals. Detailed physical models are not suitable because they require a lot of detailed structural and geometrical information which is not available to every wind turbine operator in practice. Furthermore, detailed models imply the necessity of high-resolution time series. However, SCADA-data is normally delivered at a sampling frequency of 0.001 Hz. Applying regression techniques bares the advantage that such models do not need detailed structural information of the turbine, however, regression models are not able to reproduce the non-linear behavior of the turbine structure. Separate regression models would be necessary for each load bearing component of interest, which in turn would result in a high amount of manual work setting up the regression models. Another possible data analysis technique for SCADA-signals would be state-observers or the application of ANNs. Both approaches need a suitable pattern recognition system to predict all transient events and non-linear behaviors of the wind turbine structure. Furthermore, both stand or fall with accurate training data of the wind turbine behavior in all relevant load cases and situations at the specific site. In practice, this circumstance cannot be guaranteed. Therefore, both models are not suitable for a practical on-condition load counting procedure to track remaining useful lifetime reserves but might be for more sophisticated and detailed load design analysis.

Simplified engineering load transfer models showed to be most suitable for an online fast fatigue check. At IABG mbH in Ottobrunn with participation of the author of this dissertation, three basic modules were developed for the wind turbine's main load bearing and transferring components: rotor, drive-train, and tower. The modules for rotor and drivetrain, were named FATIWIND.

The three most relevant load types for the drive train of a wind turbine system are the rotational bending moments of the driving shaft, the wind thrust force on the drive train elements, and torsional moments in the drive train system. The rotational bending moments of the driving shaft were identified as the most critical. Figure 4-39 shows a schematic sketch of the FATIWIND model for drive train components.

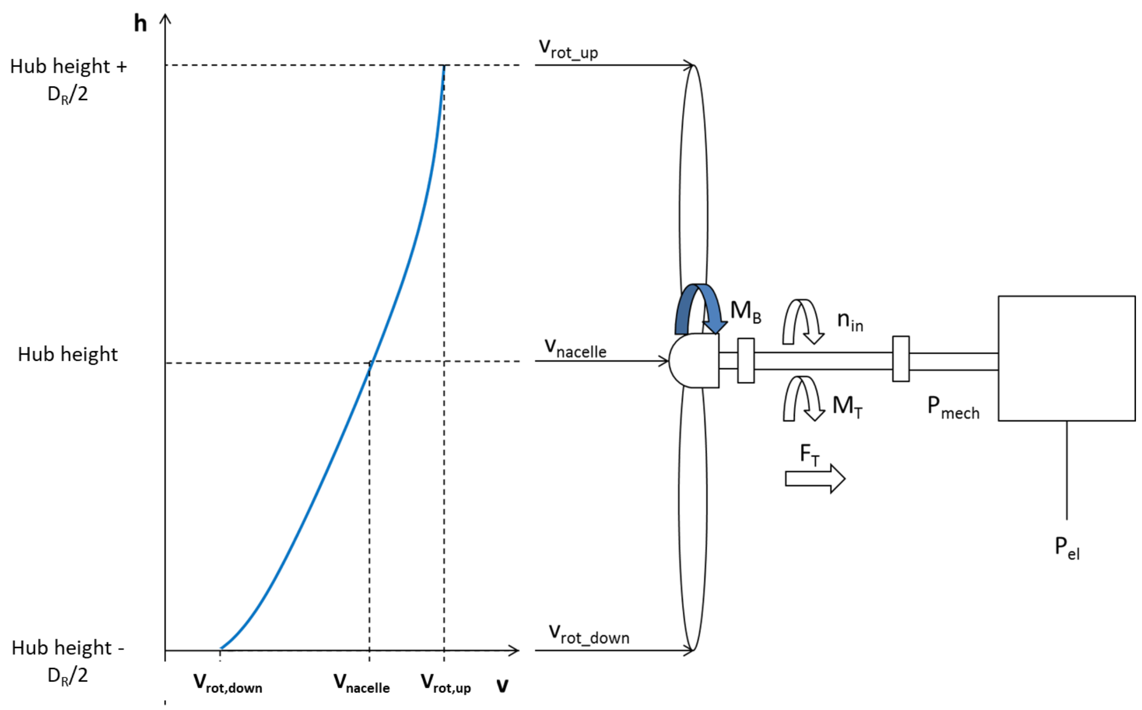


Figure 4-39: Schematic sketch of FATIWIND model for drive train components

The calculation of the rotational bending moment of the driving shaft is based on the provision of different wind speeds over the rotor plane according to the wind speed elevation profile assumption introduced in chapters 2.1 and 2.4.

Theoretically, all relevant loads could be calculated using the airfoil theory (Gasch et al. 2007), however, in practice it is not possible to retrieve all relevant wind inflow information - angle of inflow, etc. – from the SCADA data channels. Therefore, the simplified engineering load transfer model applies a few simplifications to process SCADA-data for a fast fatigue load analysis.

The analysis tool assumes that the wind turbine rotor acts like a rotor disc due to the equal distribution of 120° of each rotor blade. Considering the thrust force of the incoming wind flow and the described wind inclination over height, it is also assumed that the action point of the rotational bending moment is offset to the upper part of the rotor disk. The wind gradient implies a dominant load factor for wind turbines with great hub heights, as is predominantly the case for onshore wind turbines. The simplifying assumptions of the FATIWIND-model are graphically explained in in Figure 4-40.

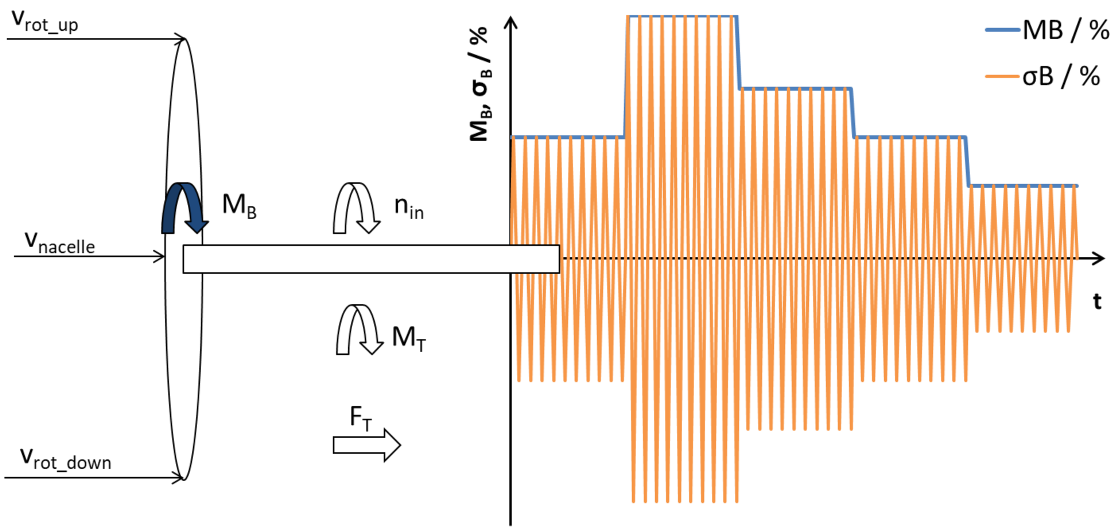


Figure 4-40: Rotational bending moment model in the FATIWIND drive train model

Considering the wind inclination profile, the algorithm calculates the overall sum of the positive rotational bending moment in the upper sphere of the rotor disc and the negative rotational bending moment in the lower part of the rotor disk. The resulting – positive – rotational bending moment is transferred as load parameter into a classic structural durability analysis module. The operational SCADA load time series are binned into 256 load classes. Subsequently, the relative frequency of load cycles is determined for every load category.

Due to the fact that in most practical situations the operators will not have detailed fatigue design load information, the algorithm uses the generation of an individual fictive S-N curve as fatigue limit for the respective component. The procedure uses the probability distribution of wind speed at the respective wind turbine site and other fatigue relevant information out of the site assessment, which is in almost all cases available to the operator. As introduced in chapter

2.1, most wind speed site assessment deploy a *Weibull* probability distribution to describe the wind load conditions at site. The classic *Weibull* distribution can be described mathematically as follows.

$$f(v) = \frac{k}{A}\left(\frac{v}{A}\right)^{k-1} \cdot e^{-\left(\frac{v}{A}\right)^{k}}$$

Whereby:

k … shape parameter

A … scaling parameter

Equation 4-14

The FATIWIND module was presented and discussed at the remaining useful lifetime working group of the German wind energy association (Arbeitskreis "Weiterbetrieb" des Bundesverband Windenergie e.V.).

In a show case study performed by IABG, sample data from a selected wind turbine was used for the generation of a fictive S-N-curve and consecutive wind turbine site assessment, as follows:

- Shape parameter $k = 2.28$
- Scale parameter $A = 6.5\ m/s$
- Annual average wind speed = 5.9 m/s

Figure 4-41 shows the different probability distribution of the case study.

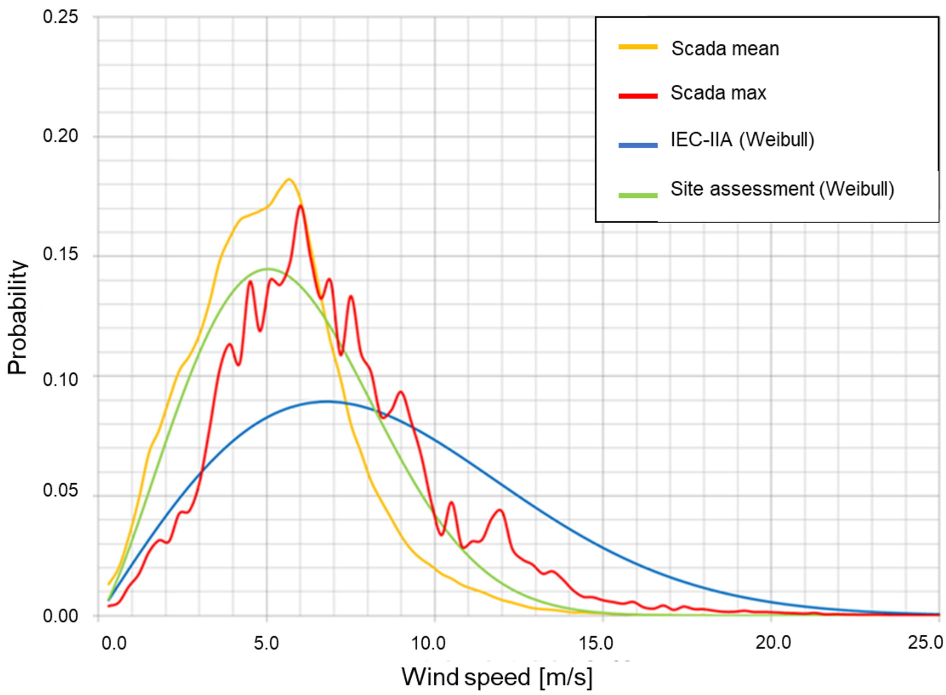


Figure 4-41: Wind speed probability distributions of the FATIWIND case study [Source: IABG]

If specific site information is not available it is also suitable to deploy general data from the IEC site classifications, which are publicly available. Due to the fact that the fatigue limit state information is not considering individual site-specific information, the approach deploying IEC site classification data can be considered as more conservative. In the sample case IEC sourced data would be $k = 2$ for the shape parameter and $A = 9.6\ m/s$ for the scale parameter.

Figure 4-42 displays the general procedure of the modules graphically.

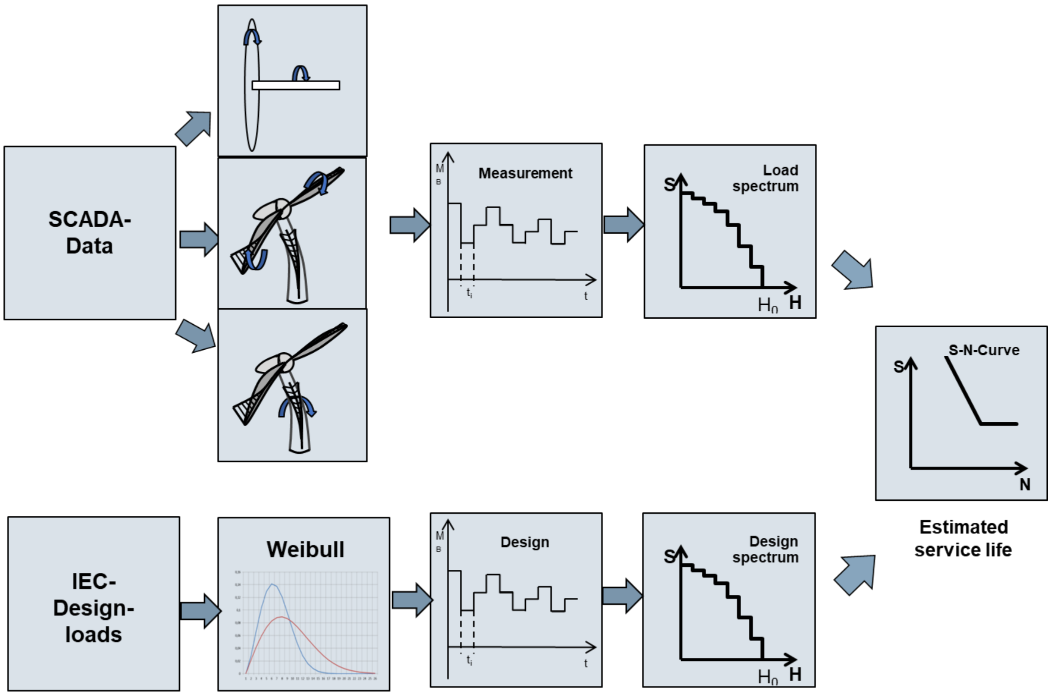


Figure 4-42: Fast fatigue check modules of IABG‘s FATIWIND method

The upper part of the procedure leads through three engineering-based load transferring models for drive train components, rotor blades, and tower structure parts from SCADA data input to measurement load spectrums. The lower part of the procedure aims to generate and derive suitable design load spectrums out of the IEC site classification and prognosed wind loading at site. Figure 4-43 displays the rotational bending moment measurement spectrum from the FATIWIND drive train model for eleven operational years of the reference turbine. It is clearly visible how different the single contribution of the different wind years is, considering the overall fatigue damage of eleven years.

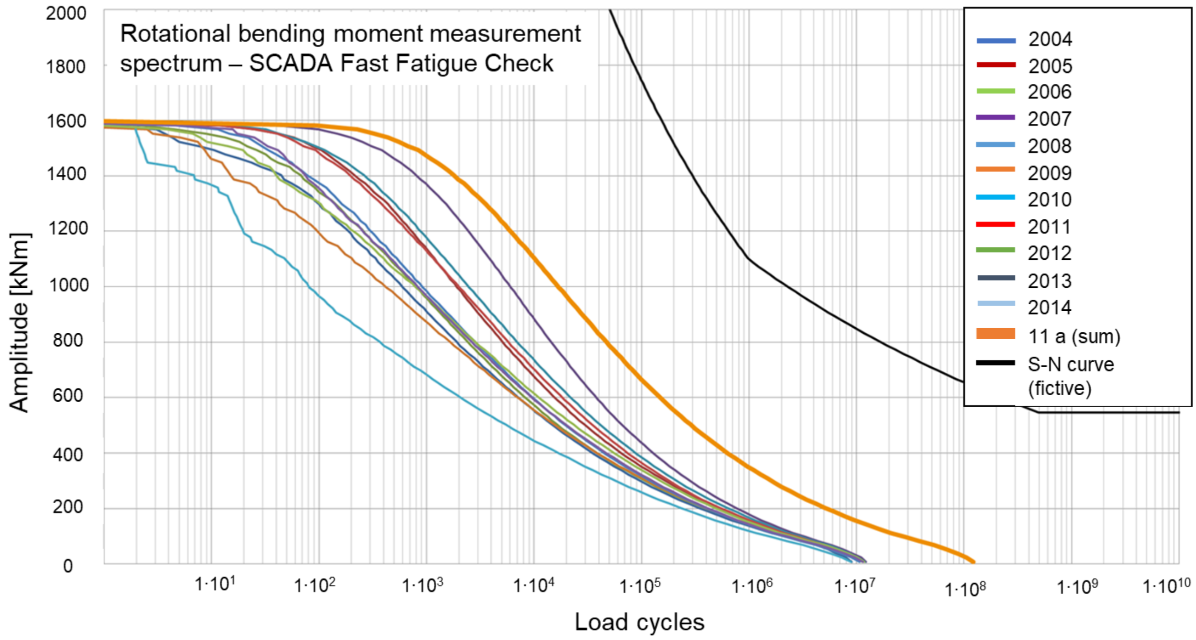


Figure 4-43: Rotational bending moment measurement spectrum – FATIWIND [Source: IABG]

Figure 4-44 displays the rotational bending moment design spectrum from the FATIWIND drive-train model for eleven operational years of the reference turbine. The eleven years of SCADA load spectrums were used as a basis for extrapolation to a 20-year model, which is generally assumed as design service life of wind turbine structures. First it can be deducted that with the current load extrapolation basis, taken the distributional parameters of the site assessment, the damage accumulation effect of higher and extreme loads would be underestimated. However, site assessment data should only be used as additional data source to classify the overall results, because the data source and assumptions for site assessments are not always transparent and (at least in Germany) often lack accuracy. On the other hand, the IEC design load assumptions derived from the IEC site classifications and the respective parameters can be taken as reference level for the consumed service life of the respective component in a fast fatigue check based on SCADA-data of the wind turbine.

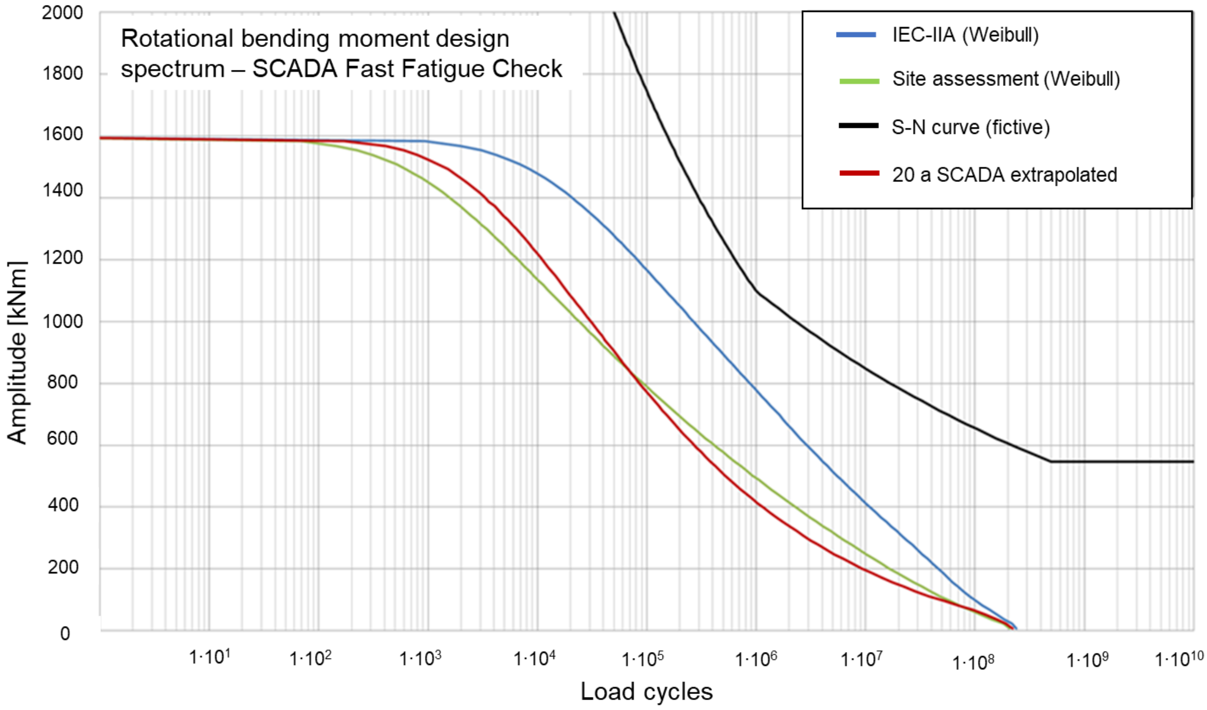


Figure 4-44: Rotational bending moment design spectrum – FATIWIND [Source: IABG]

Taking the IEC load assumptions as fatigue design reference, the drive train shaft of the reference wind turbine will have a safe service life of 92 years based on the current SCADA-data basis. However, taking the most damaging wind year 2007 as extrapolation basis, the service life of the drive-train shaft would only be 17 years. This uncovers three basic findings.

On the one hand, after a little over half of the designed service life, the indications of service lifetime reserves in major wind turbine components are quite strong. On the other hand, the very high variation of wind loading depending on the year made quite obvious that a significant amount of data is needed for a trustworthy analysis of a remaining useful wind turbine service life and that using only short time measurement campaigns as extrapolation basis can be quite dangerous and fatal. Thirdly, applying already existing SCADA-data as input for fatigue life estimations can be useful, especially if more sophisticated data is not available (e.g. older turbine types, lack of documentation, etc.).

Figure 4-45 displays the blade root bending moment measurement spectrum in fore-aft direction from the FATIWIND blade model for eleven operational years of the reference turbine. The fore-aft bending generally shows to be the highest loading for the blade root and is therefore chosen for the critical load path in the blade model. In accordance with the findings in Figure 4-43 the most obvious result is the high variation of load contribution of each wind year to the overall accumulated damage.

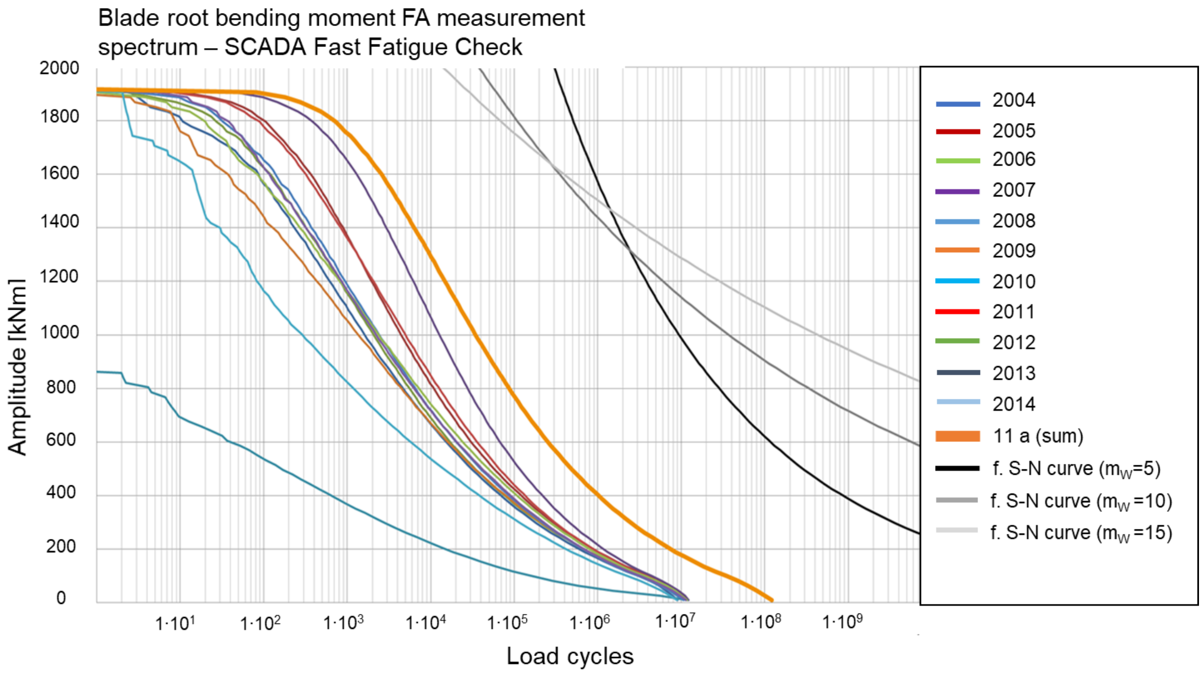


Figure 4-45: Blade root bending moment FA measurement spectrum – FATIWIND [Source: IABG]

Figure 4-46 displays the blade root bending moment measurement spectrum in fore-aft direction from the blade model for eleven operational years of the reference turbine. The blade loading analysis demonstrates the same characteristics for a fast fatigue analysis of the drive train shaft. However, the analysis of the blade model is more complex, because the blade root is built in composite material for which it is generally more difficult to find adequate fatigue assumptions on a component level. Therefore, the analysis must make further assumptions to retrieve results on component level. Further assumptions always induce more uncertainty in the model. However, as the fast fatigue analysis is not aiming to claim a final and sophisticated remaining service life result with high accuracy, further assumptions are worthwhile to analyze past consummations of service life or material resistance with available SCADA-data. For a better classification of the results the blade module works with different S-N exponents (k=5; k=10, k=15). Applying an averaging assumption and taking the current SCADA-data basis into account, the FATIWIND module analyzes the blade's component safe service life to be only 16 years. The rather high uncertainty of the analysis notwithstanding, this implies that the rotor blade system for the reference turbine is rather to be replaced in order to guarantee a safe service lifetime extension for the reference turbine. Thus, it can be concluded that some main load bearing components may need to be replaced for a safe service lifetime extension of wind turbine systems. Furthermore, it becomes apparent that the overall maintenance costs of wind turbine systems capable of service lifetime extension are the most important parameter.

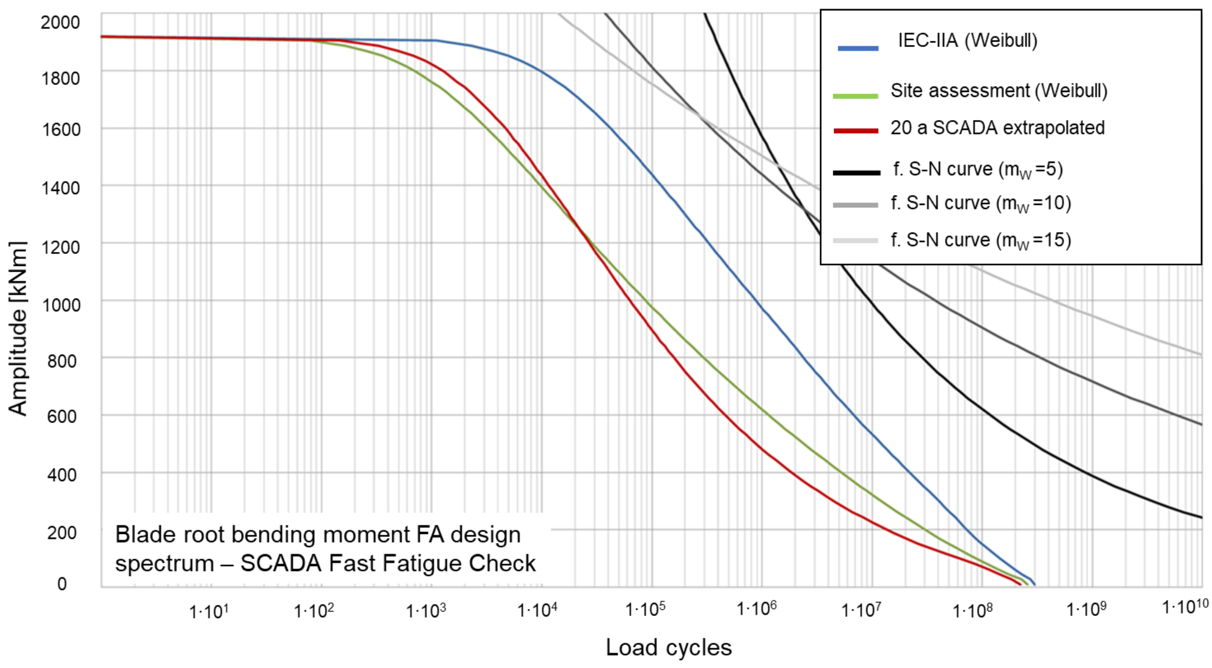


Figure 4-46: Blade root bending moment FA design spectrum – FATIWIND [Source: IABG]

Aiming to apply the fast fatigue check approach to the tower structure of a wind turbine, the fatigue analysis must also be conducted on a sub-system level. Fatigue checks for a hybrid and prestressed concrete tower construction must be evaluated for the concrete part, the reinforcement system, as well as for the prestressing steel elements (Grünberg and Göhlmann 2013). Derived from experience in civil engineering – and especially from experience on structural stability of bridges – the prestressing steel elements and their connecting elements can be seen as fatigue hot spots, also for the structural design of wind turbine hybrid towers. The tower FFC module focusses on a hybrid wind turbine tower structure designed as a prestressed concrete construction. Considering the tower module, it was possible to access a more detailed SCADA-data level and to retrieve tower top acceleration data in a resolution of 0.1 Hz. The discrete data sets were interpolated to simulate a continuous time series of tower acceleration data. Subsequently, the acceleration values were integrated twice for tower top displacement time series. Calculation and classification of the resulting displacement spectrum is performed applying the *Rainflow* counting algorithm under the assumption of linear damage accumulation theory as introduced in chapter 2.4.2. Accordingly, the resulting geometrical displacements must be transferred onto the stress-strain dimension of the prestressing steel elements. The displacement behavior of the prestressing elements is dependent on the specific tower design. Figure 4-47 shows different possible displacement behavior categories according to the tower design, which were initially developed in collaboration with the student thesis of Jens Habegger.

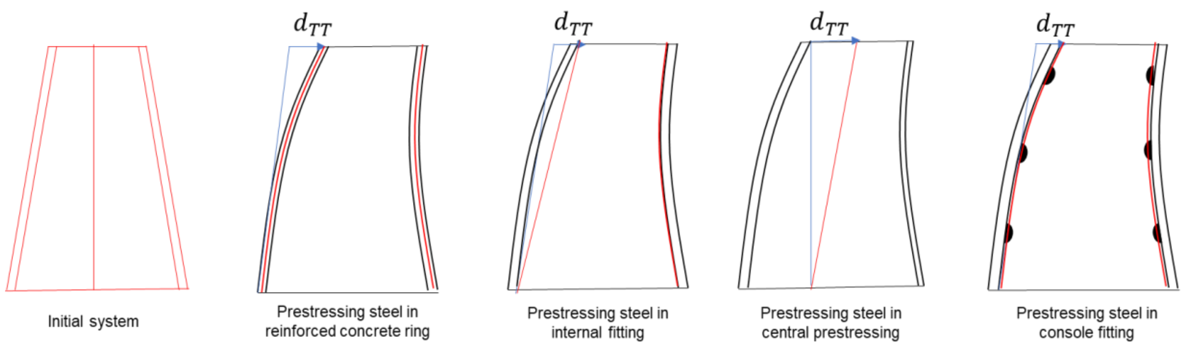


Figure 4-47: Different type of prestressing steel elongation in different tower design concepts

The new length of the prestressing elements due to a tower top displacement can be calculated applying the following mathematical model.

$$l_{TL} = \begin{cases} \sqrt{l_0^2 + {d_{TT}}^2} \text{ ... } linear \\ \int_0^{l_0} \sqrt{1 + \frac{4{d_{TT}}^2 x^2}{l_0^4}} dx \text{ ... } parabolic \\ \sum_{i=1}^{n+1} \sqrt{(\frac{l_0}{n+1})^2 + \left(\frac{d_{TT}}{l_0^2}\left(\frac{l_0}{n+1} i\right)^2 i - \frac{d_{TT}}{l_0^2}\left(\frac{l_0}{n+1} i_{-1}\right)^2\right)^2} \text{ ... } polygonal \end{cases}$$

Whereby:

d_{TT} … Tower top displacement

Equation 4-15

Based on Equation 4-15 it is possible to calculate the strain of the prestressing steel elements:

$$\varepsilon_T = \frac{l_{TL,new} - l_{TL,0}}{l_{TL,0}}$$

Equation 4-16

Under the assumption that the resulting stresses do not exceed the yield strength of the prestressing steel elements, the following relationship between stress and strain can be assumed (EN1992):

$$\sigma = \varepsilon_T E$$

Equation 4-17

Wind turbine towers in prestressed concrete designs are to be assumed as critically damped systems with a logarithmic damping increment of 0.05. Therefore, periodic displacement will only occur with a very low probability. Thus, the stress range must be considered for every displacement separately (Burton et al. 2011).

Considering the fatigue resistance capacity of the respective tower structure, the S-N design laws and the Palmgren-Miner assumptions of linear damage accumulation are also the underlying basis for the tower FFC module. This states that for every stress range there is a maximum number of stress cycles which the prestressing element can resist without failure. The remaining useful lifetime estimation is then based on a comparison of the actual experienced stress cycles of the prestressing element in the respective stress range and the maximum amount of stress cycles within the respective stress range that the element can resist. Performing the FFC tower module under this assumption, the maximum amount of stress cycles for every calculated strain value is calculated applying a characteristic S-N curve (EN1992). The determination of the respective parameters in sample residues is already performed under the assumption of a specific outlier probability (ISO 12107:2012). Figure 4-48 displays the applied characteristic strength curve.

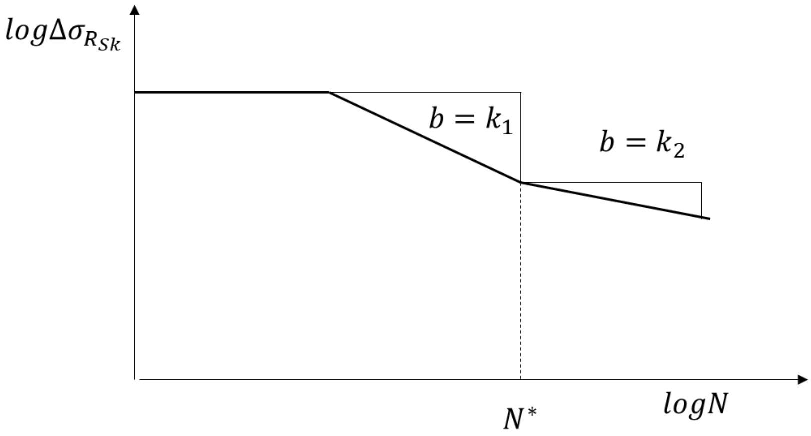


Figure 4-48: Characteristic strength curve of prestressing steel

The parameters $\Delta\sigma_{R_{Sk}}$ and N^*, as well as the gradient parameters k_1 and k_2 are directly dependent on the specific composite, as well as on the specific detailed design and can be retrieved from Annex A of EUROCODE 2 (EN1992).

The final estimation of the remaining useful lifetime of the tower structure can be performed with the following mathematical model:

$$D = \sum_i \frac{n(\Delta\sigma_i)}{N(\Delta\sigma_i)} < 1$$

Equation 4-18

And it follows:

$$t_{RUL} = \frac{t_{meas}}{D} - t_{op}$$

Equation 4-19

In all analyzed load scenarios, the RUL of the tower was 1.5 … 3.5 times the design life, which confirms the above made assumptions of the tower being the basis for extended lifetime concepts and tending to bear the necessary material resistance reserves.

4.6.2 FLEET LEADER CONCEPT

The loading of a wind farm is location specific, this is true on micro scale for the location of a single wind farm in a wind park as well as on macro scale for the location of a single wind turbine in the respective wind zone in the countryside. This suggests that during the service life of a specific wind turbine type in different locations, certain components will wear faster and others slower. The idea of a fleet leader is to make use of such information to adjust maintenance and inspection tasks according to the real loading of the turbines – instead of assuming similar degradation behavior for all turbines. Highly loaded components might need earlier changes to ensure the wind turbine's availability. For components under lower loading conditions, operators might consider skipping or postponing maintenance actions and adjusting them to the components' actual wearing condition. The goal should be to seek an optimal balance between maintenance actions and the gained availability and reliability of the wind turbine. One way to get insight in the loading of all components of a wind turbine is the complete instrumentation of the wind turbine's critical components. However, in most cases this is the most expensive and time-consuming way. Unless for research purposes - e.g. to use a completely instrumented turbine for model and design assumption verifications (Geiss 2013) - this cannot be the approach to economically optimize maintenance strategies for wind turbines. Thus, the fleet leader concept envisages equipping only a few or even only one single turbine with additional load sensor systems and establishing relations between the fatigue load measurements of the so-called fleet leader turbine and the operational data or SCADA-data of all fleet member turbines. Once the relations are known for the fleet leader, they can be combined with the SCADA-data of the fleet member turbines, thus enabling operators to extrapolate and calculate the accumulated loading on all turbines. Figure 4-49 displays the basic idea of the flight leader concept graphically.

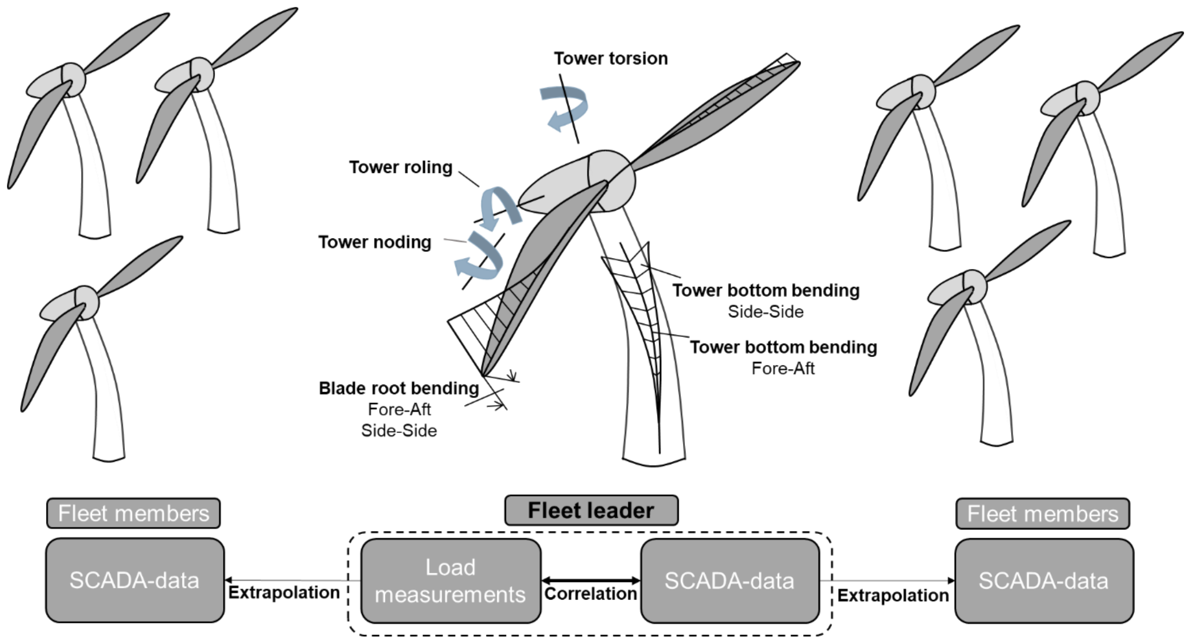


Figure 4-49: Fleet leader concept – adapted from (Obdam et al. 2009)

SCADA-data is delivered in 10-minute average statistical values. The load measurements are delivered in continuous time series and need to be processed to calculate loads on a 10-minute average basis. Core SCADA-data channels for the fleet leader concept are the following:

- Turbine operational mode
- Wind speed
- Wind direction
- Electrical power output
- Generator speed
- Yaw direction
- Pitch angle

Furthermore, a wind turbine operates in different power production modes or load cases, which must be differentiated in the load analysis. Table 3-1 displays possible load case and turbulence condition combinations, which are found by Obdam et al. (2009).

Table 4-6: Fleet leader load case differentiation

ID	Load case	Wake condition / Turbulence
1	Normal power production	Free-stream
2		Partial wake
3		Full wake
4	Parked / Idling	-
5	Start-up	
6	Normal shut down	
7	Emergency shut down	

The load time series are processed using the theory of damage equivalent loads (DELs) as described in chapter 2.4.

Should the empirical SCADA-database be too small for an adequate extrapolation, simulation data can be used. However, the situation of missing data cannot be avoided completely in practical application of the concept. Therefore, a handling procedure for missing data is required. To correlate and cluster the load measurements with the SCADA-data for the fleet leader turbine, regression models are used. Possible methods are the second order polynomial, potential least squares, or the application of artificial neural networks (ANN). Obdam et al. (2009) claim that ANNs are the most suitable estimation technique for this purpose. Next, the validity of the load predictions is evaluated by comparing the measured load accumulation with the predicted load accumulation for the fleet leader turbine. Figure 4-50 depicts the process flow chart of the SCADA-Fleet-Management-Concept (SCADA-FMC).

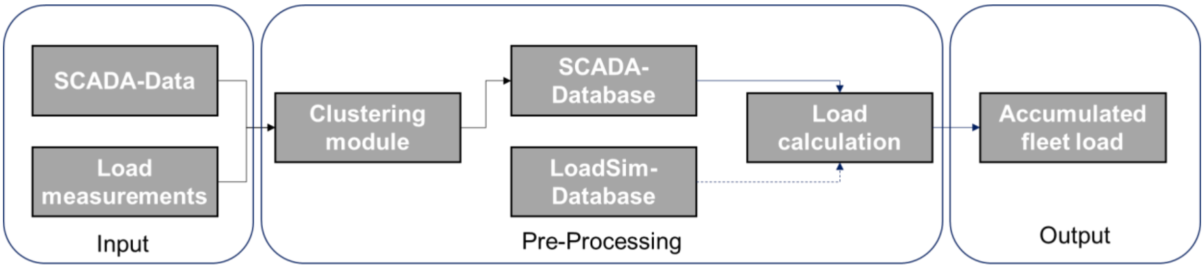


Figure 4-50: Process flow chart of SCADA-FMC – adapted from (Obdam et al. 2009)

Furthermore, the SCADA-FMC needs to consider an outlier treatment, if outliers are identified in the database. The calculated value of a load indicator can never be smaller or larger than a certain factor α_{FL} multiplied with the minimum or maximum measured value of the loading.

$$(1-\alpha_{FL}) \cdot \min(\Delta F_{EQ,i_{FL}}) \leq \Delta F_{EQ,i_{FL}} \leq (\alpha_{FL}+1) \cdot \max(\Delta F_{EQ,i_{FL}})$$

Equation 4-20

The next step is intended to ensure that for all turbines an equal amount of data exists. Missing values are estimated by taking the average value of the loading h_a of all turbines in the fleet for which the respective loading is known.

$$\Delta F_{EQ,h_a,i_{unavailable,t}} = \frac{1}{n} \sum_{i,available}^{n} \Delta F_{EQ,h_a,i_{available,t}}$$

Equation 4-21

The load accumulation of each turbine in the fleet leader concept is calculated as follows:

$$\Delta F_{total,i} = \sqrt[m_W]{\sum_{i=1}^{n} \Delta F_{i,t}^{m_W}}$$

Equation 4-22

Whereby $\Delta F_{i,t}$ is the load component for turbine i and 10-minute time stamp. Subsequently the relative difference is calculated.

$$Difference = \frac{\Delta F_{total,i} - \Delta F_{total,iref}}{\Delta F_{total,iref}}$$

Equation 4-23

The results are validated on the fleet leader turbine by comparing the predicted values with the measured values.

$$Error = \frac{\Delta F_{total,pred} - \Delta F_{total,meas}}{\Delta F_{total,meas}}$$

Equation 4-24

The nacelle anemometer is most likely the greatest source of error when applying the fleet leader concept. Therefore, a calibrated tower top anemometer is essential (Peters et al. 2012; Cosack 2010). However, it has to be taken into account, that this measurement information is only valid for the specific anemometer location on the nacelle top.

4.6.3 RISK-BASED SUSTAINABLE MAINTENANCE STRATEGIES

To answer research question **RQ 8**, the following sections display the findings:

Which concept is suitable to combine monitoring and inspection techniques in one holistic approach?

The concept of risk-based inspection strategies is defined as monitoring level 3 and completes the multi-level monitoring concept introduced in chapter 4.6. Furthermore, the methods presented here can be used as implementation guideline for the probabilistic approach to determine the remaining useful lifetime of wind turbine systems, as defined in the DNVGL guidelines for service life extension of wind turbines introduced in chapter 2.4.3. The basic composition of risk-based inspection strategies is intensively described in (Faber et al. 2000; Straub 2004; Thöns et al. 2015; Raiffa and Schlaifer 2000; Maljaars et al. 2012; Sorensen). The following sections will introduce the basic concepts and transfer the relations as implementation framework to combine monitoring and inspection techniques in a holistic asset management approach for the supporting structure of existing onshore wind turbines, with the aim to optimize the relationship between availability and maintenance cost at an optimal usage of resistance reserves. The ultimate goal is to use service life reserves sustainably (Geiss and Grosse 2018).

While qualitative maintenance optimization models are limited in determining which maintenance strategy is the most cost-effective option, mathematical maintenance optimization techniques alone do not ensure that maintenance efforts focus on the right components. By merging these two approaches, monitoring level 3 provides probabilistic instruments for the evaluation of a damage tolerant remaining useful service life of wind turbine structures. The concepts described herein are implementation examples of the “probabilistic approach” to determine the remaining useful service life of a structure as suggested by the GL guideline described in chapter 2.4.3. Furthermore, Bayesian updating techniques will be presented which can be used to combine information of the “practical part” with the probabilistic approach based on structural reliability analysis. However, the RBI approach presented here is only one step in the IAMS-Wind concept, otherwise leading to a high risk of gross errors and misjudgments if only detailed failure mechanisms and deterioration processes are analyzed.

Risk is the probability that a specific event will occur multiplied be the event’s consequences, given a specific activity and the activity only having one consequence.

$$R = \sum_{i=1}^{n} P_i C_i$$

Equation 4-25

The concept of risk-based inspection planning inherits the primary goal of quantifying the effect of inspections on the risk condition of a component and thus enables cost optimal inspection planning. Given the fact that design deterioration laws represent imperfect knowledge considering the component's deterioration process in service, risk-based inspection planning is a suitable method for deterioration control under in-service conditions.

The approach presented here combines Bayesian decision analysis with structural reliability analysis. Available probabilistic models of the deterioration process and the inspection performance are used to present a consistent decision basis. Deterioration processes of structures are of highly stochastic nature. Models describing these processes involve large variations and uncertainties. The method of uncertainty quantification has two main objectives, first the quantitative characterization of uncertainties and second the reduction of uncertainties.

There are two different sources or categories of uncertainties, aleatoric uncertainties and epistemistic uncertainties. Aleatoric uncertainties represent statistical uncertainties or the unknowns each time an experiment is run, e.g. wind speeds, sea states or the fatigue crack growth. Epistemistic uncertainties describe systematic uncertainties including data and model uncertainties. When the modeled problem is observed, the problem turns into an epistemistic uncertainty problem and therefore enables uncertainty updating.

Inspections can reduce those uncertainties and update the incomplete knowledge of the state of nature, which can be described as an epistemistic uncertainty. In many applications in asset management of structures, inspections can be a cost-effective risk reduction measure.

The concept of risk-based inspections focusses on the goal of optimal allocation of deterioration control. Existing quantitative models vary substantially dependent on the context or the industry they are applied in. Most published RBI models for structural systems are based on fully quantitative probabilistic deterioration models combined with Bayesian updating.

Empirical statistics for structural systems – especially in the wind industry - are rarely available, because every structure is more or less unique. Therefore, the experience with structural failures is scarce. Qualitative estimations for the impact of inspections on the probability of failure are therefore not suitable. Furthermore, the RBI-approach assumes that fatigue only occurs in hot spots.

To introduce the risk-based inspection concept, the Probabilistic Model Code (Joint Committee on Structural Safety 2001) gives an illustrative example for a steel bar:

The crack growth model is assumed as follows:

$$a(n) = a_0 \exp(C\pi s^2 n)$$

Equation 4-26

Given C as material parameter for steel: $C = 5 \cdot 10^{-5}$

Further on, it is assumed, that the steel bar fails at a crack length of 40 mm. The loading of the steel bar is given by the normal distributed stress range S, with parameters $\mu_S = 30MPa$ and

$\sigma_S = 5MPa$. The number of load cycles per year is 10^5. An initial defect is modelled with an exponential distributed random variable with the parameters $\mu_{A0} = \sigma_{A0} = 1\ mm$.

The minimum requirement considering the annual probability of failure is an annual failure probability of 10^{-4}. An inspection should be planned a year before the threshold is reached. As an additional source of uncertainty, the uncertainty of the applied inspection methods must be considered. The probability of inspection (POD) is given by $\mu_{POD} = \sigma_{POD} = 1\ mm$, assuming an exponential distribution.

An inspection update in year six of the steel bar's service life, assuming no crack was found, is described as follows:

$$P(a_{crit} - a(n) \leq 0 | a(n) - POD \leq 0) = \frac{P(a_{crit} - a(n) \leq 0 \cap a(n) - POD \leq 0}{P(a(n) - POD \leq 0)}$$

Equation 4-27

Figure 4-51 describes the progress of the original probability of failure versus the updated probability of failure for the steel bar example.

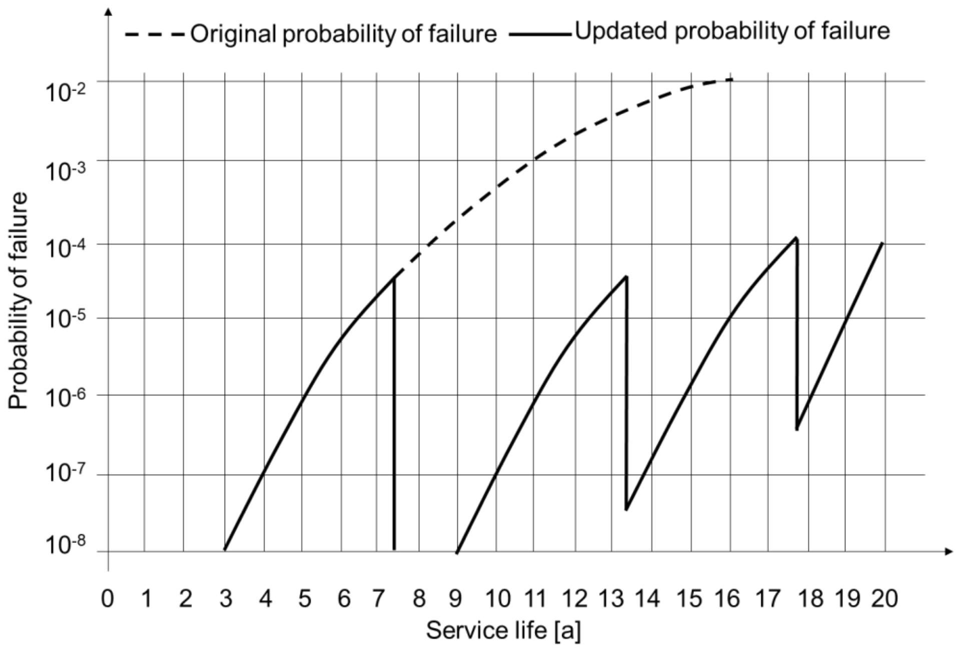


Figure 4-51: Original probability of failure vs. updated probability of failure for steel bar example

The offshore industry proved to be a catalyzer for the development of risk-based inspection methods. A concise history of risk-based inspection approaches can be found in Straub (2004).

Generally, probabilistic model building can be subdivided into the four following and consecutive steps:

1) Assessment and statistical quantification of available data
2) Selection of distribution function
3) Estimation of distribution parameters
4) Model verification
5) Model updating

Figure 4-52 displays the basic steps of probabilistic model building graphically.

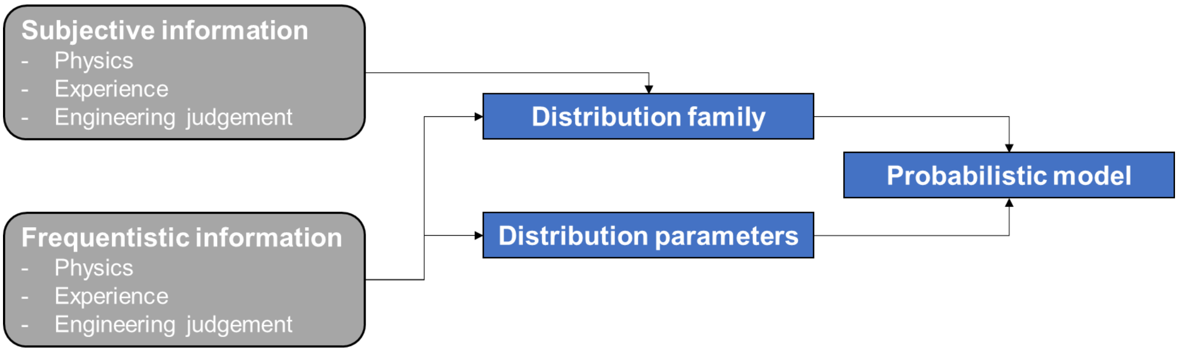


Figure 4-52: Basic steps of probabilistic model building – adapted from (Straub 2004)

The failure probability for a period of time t can be expressed as follows:

$$P_F(t) = P[min\ g(x(\tau);\tau) < 0\ for\ 0 < \tau < t]$$

Whereby:

- g is the limit state function
- $x(\tau)$ is the vector of basic variable at time τ

Equation 4-28

The reliability of the system is defined with the following expressions:

$$r(t) = \frac{P(failure\ in\ [t, t + \Delta t]|survival\ up\ to\ t)}{\Delta t} = \frac{p_F(t)}{1 - P_F(t)}$$

Equation 4-29

And for $p_F(t)$:

$$p_F(t) = \frac{dP_F(t)}{dt}$$

Equation 4-30

The mean time to failure is defined as:

$$\mu = \int_0^\infty t p_F(t) dt = \int_0^\infty (1 - P_F(t)dt)$$

Equation 4-31

The general deterioration process can be modelled as follows:

$$\frac{dy}{dt} = y^{k_{PN}} h(z)$$

Equation 4-32

Whereby:

- $y(t)$ is the damage indicator
- $z(t)$ is a random process of disturbances
- h is a positive definite function of z
- k_{PN} is a parameter determining the nature of the process

Therefore, one can derive:

$$\int_{y(0)}^{y(t)} y^{-k}\, dy = \int_{0}^{t} h\big(z(\tau)\big) d\tau$$

Equation 4-33

And for $\chi(t)$:

$$\Psi\big(y(t)\big) - \Psi\big(y(0)\big) = \chi(t)$$

Equation 4-34

Whereby:

- $\Psi(y)$ is the integral function of y^{-k}
- $\chi(t)$ is integral of $h\big(z(\tau)\big)$

If z(t) is stationary and ergodic, $\chi(t)$ may asymptotically be taken as implying that the damage increases smoothly.

$$\chi(t) = tE\big\{h\big(z(t)\big)\big\}$$

Equation 4-35

Failure will occur when damage exceeds a critical value, therefore the limit state functions results as follows:

$$g(t) = \Psi\big(y_{cr}(t)\big) - \Psi\big(y(0)\big) - \chi(t)$$

Equation 4-36

If y_{cr} is time dependent we have a first passage problem.

The fatigue crack propagation can be modelled with the following equation:

$$\frac{da}{dn} = CY(a)\big[\Delta S(n)\sqrt{\pi a}\big]^{m}$$

Equation 4-37

Whereby:

- ΔS is represents the stress range
- $Y(a)$ is represents a geometrical function
- C is a material constant
- m is a material constant
- n is the stress cycle number
- t can be replaced by n / k can be replaced by $m/2$

$$\Psi = \frac{2}{2-m}\frac{1}{CY}\pi^{-m/2}p^{-m/2}a^{1-m/2}$$

Equation 4-38

If ΔS assumed as stationary and ergodic, it follows:

$$\chi = nE\{(\Delta S)^m\}$$

Equation 4-39

Therefore, the limit state function constitutes as follows:

$$g(t) = \psi(a_{cr}) - \psi(a_0) - \chi$$

With:

- a_{cr} as critical crack length
- a_0 as initial crack length

Equation 4-40

If the problem is time dependent we must consider a first passage problem. The problem formulated in the crack domain can be expressed as follows:

$$g(t) = a_{cr} - a(n) \text{ with } a(n) = \left\{a_0^{1-m/2} + \frac{2}{2-m}CY\pi^{m/2}nE\{\Delta s^m\}\right\}$$

Equation 4-41

The problem formulated in the time domain can be expressed as follows:

$$g(t) = N - n \text{ with } N = \frac{\psi(a_{cr}) - \psi(a_0)}{E\{(\Delta S)^m\}}$$

Equation 4-42

In many situations the conditional probability of specific events is of interest, meaning the probability of occurrence of event E_2 given the occurrence of Event E_1. Figure 4-53 displays a generic example. This classic probabilistic dependency is generally handled with *Bayes'* rule:

$$P(E_2|E_1) = \frac{P(E_1 \cap E_2)}{P(E_1)} = \frac{P(E_1|E_2)P(E_2)}{P(E_1)}$$

From this basic equation one can derive definitions for the RBI framework:

- $P(E_1|E_2)$ is the likelihood measure for the amount of information on E_2 gained by knowledge of E_1. The likelihood measure is typically used to describe the quality of an inspection.
- $P(E_2|E_1)$ is known as the posterior probability of occurrence of E_2 or its updated occurrence probability.
- $P(E_2)$ is the prior probability of Event E_2, prior to the knowledge of E_1.

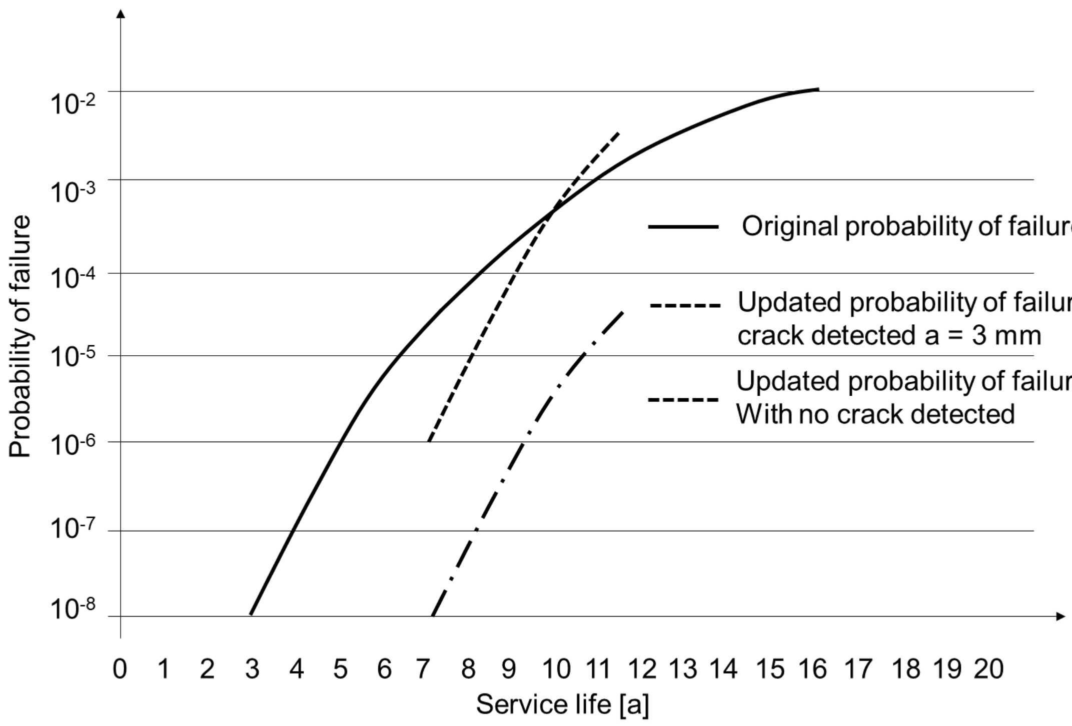


Figure 4-53: Generic example of updated probability of failure depending on inspection result

In the probabilistic RBI framework, different inspection outcomes or results are possible. Those different inspections results trigger different maintenance actions, which are also to be described by limit state functions. As relevant inspection outcomes in the RBI framework the following outcomes can be defined:

- Event of indication of a defect E_I
- Event of detection of a defect E_D
- Event of false indication E_{FI}
- Event of a defect measurement with a measured size s_m E_{s_m}

The probability of indication of a defect at an inspection can be described as follows:

$$P(E_I) = P\left(g_i\left(\underline{X}\right) \leq 0\right) = \int_{g_i(\underline{X})\leq 0}^{\infty} f_{\underline{x}}(\underline{x})\mathrm{d}\underline{x}$$

Equation 4-43

Each measurement event is different and unique. In probability theory each measurement event represents an equality event, for which the probability of occurrence can be defined by:

$$P\left(g\left(\underline{X}\right)\right) = 0 \rightarrow \text{for all measurement events accordingly}$$

Equation 4-44

And for $P\left(E_{s_m}\right)$:

$$P\left(E_{s_m}\right) = P\left(g_M\left(\underline{X}\right) = 0\right) = \int_{g_M(\underline{X})=0}^{\infty} f_{\underline{x}}(\underline{x})\mathrm{d}\underline{x}$$

Equation 4-45

The probabilistic framework of the RBI method is based on classic decision trees. Each event in the decision tree represents the intersection of events in the probabilistic view.

$$P(E_1 \cap E_2) = P\big(g_1(\underline{X}) \leq 0 \cap g_2(\underline{X}) \leq 0\big) = \int_{(g_1(\underline{X})\leq 0 \cap g_2(\underline{X})\leq 0)}^{\infty} f_{\underline{X}}\,(\underline{x})\mathrm{dx}$$

Equation 4-46

Equation 4-46 shows how to calculate the probability that event E_1 – probability of a failure event - occurs together with event E_2 – no detection during previous inspection. This basic rule of the RBI framework is also valid for events with higher complexity.

The theory of structural reliability began in the 1950s with A.M. Freudenthal. Rackwitz developed methods and tools for the present application in the 1970s (Diamantidis 2001; Faber 2013).

Historically, engineers where always aware of uncertainties when designing structures. For predicting stresses Navier's principle for allowable stresses was used. Uncertainties where accredited in both the demand – stresses – and capacity – strength of the material. But it was not possible to mathematically analyze the uncertainties. That is why large safety factors of 3 to 5 were applied. In the 20th century, there was an upcoming of the probability theory. For the first time, tools for analytical treatment of the uncertainties were available. Nowadays structural reliability analysis is a well-established engineering discipline and accepted as an analytical tool in structural design. The overall goal of structural reliability analysis is to reduce uncertainty of (empirical) fatigue models (e.g. S-N laws) by information from specific sources in field like monitoring and inspection. The consequences or effects of new information on the structural state is analyzed with probabilistic methods.

The very art of structural reliability analysis is to find and identify the simplest model still able to predict the performance of a structural system with sufficient accuracy considering the model application. For every structural model the performance of the structure can be described by a limit state function g. A positive value of the limit state function $g > 0$ corresponds to a satisfactory performance of the structural system under analysis. A negative value $g < 0$ corresponds to an unsatisfactory performance or failure of the structural system. The limit state function can be defined in terms of demand S and capacity R. Failure will occur when S exceeds R. Figure 4-54 displays the classic structural reliability problem.

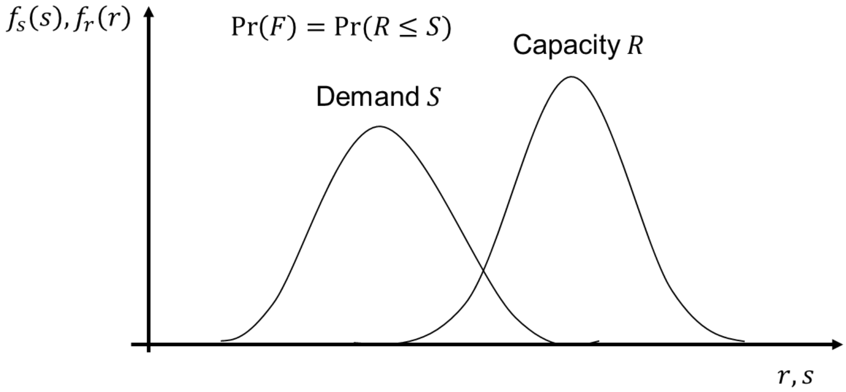


Figure 4-54: Classic structural reliability problem

The limit state function can be formulated as follows:

$$F = \{R \geq S\} = \{R - S \geq 0\}$$

Equation 4-47

Whereby:

$$g(R, S) = R - S$$

Equation 4-48

The probability of failure of the structural system can be derived as follows:

$$\Pr(F) = \Pr(g(R, S) \leq 0) = \Pr(R \leq S)$$

Equation 4-49

S and R are independent and non-negative. The probability of failure can also be expressed as integral formulation:

$$P(F) = P(R \leq S) = \int_0^\infty f_r(r) \int_r^\infty f_s(s)\, ds dr$$

Equation 4-50

For a more general formulation the limit state function, $g(\underline{X})$ is introduced. Thereby $\underline{X}$ is a vector of all random variables involved in the problem. The limit state function defines the intersection border between the safe domain where $g > 0$ and the failure domain where $g \leq 0$. Thus, the probability of failure is defined by integration over the failure domain:

$$P(F) = P\big(g(\underline{X}) \leq 0\big) = \int_{g(\underline{X}) \leq 0}^{\infty} f_{\underline{x}}(\underline{x}) \mathrm{d}\underline{x}$$

Equation 4-51

An analytical solution of the above equation exists only in special cases. However, there are different numerical approximation techniques, e.g. the Monte-Carlo-Simulation or the importance sampling technique.

Furthermore, the probability density function $f_{\underline{x}}$ $(\underline{x})$ can be simplified by introducing the reliability index β. The reliability index is represented by the negative reciprocal standard normal distribution of the probability of failure.

$$\beta = -\Phi^{-1}(p_f)$$

Whereby:

- Φ … standard normal distribution function
- p_f is equivalent to $P(F)$

Equation 4-52

The approach is based on the transformation of $f_{\underline{x}}$ $(\underline{x})$ to independent standard normal distribution functions $\varphi(u_i)$. As state-of-the-art transformation method, the so called Rosenblatt transformation is a basic tool which can be applied in this framework. An alternative method is the so called Nataf transformation. A detailed introduction of β can be found in Melchers and Beck (2018).

All deterioration mechanisms are time-dependent and consequently all reliability problems in fatigue are time dependent. A failure event of a deteriorating structure can be modelled as a first passage problem. Consequently, the limit state function is then additionally a function of time.

For most deterioration processes the problem is simplified by the fact that damage monotonously increases with time. If the modelled deterioration problem has a fixed damage limit – meaning that a failure occurs when damage reaches a constant limit – the deterioration problem can be solved as time-independent problem. The time variable t is then a simple parameter of the model and deterioration is treated as a monotonously increasing process. E.g. if failure has not occurred at time t_1, failure has also not occurred at time $t < t_1$. For the definition of a failure rate of the modelled system, several definitions are possible. In this case the annual failure probability of the modelled system is best fitting. This circumstance enables to evaluate the reliability problem at fixed time intervals $t = t_1; t_2 \dots; t_n$.

$$t = t_{i-1} + 1yr$$

Equation 4-53

Consequently, the annual probability of failure in year $t_i$can be expressed as follows:

$$\Delta p_F(t_i) = \frac{p_F(t_i) - p_F(t_{i-1})}{1 - p_F(t_{i-1})}$$

Equation 4-54

Very typical for that kind of reliability problem is the S-N fatigue modelling problem. Failure is defined to occur when the accumulated damage has reached D_{max} or commonly defined as $D_{max} = 1$.

In practical application the computation of probabilities is done with Monte-Carlo-Simulations and First-Order-Reliability-Model (FORM) algorithms, e.g. Strurel (RCP & ERACONS 2017).

The introduced probabilistic models cannot be used as mathematical basis to correlate empirical fatigue design model information (e.g. S-N laws) with inspection data from the respective hot spot on the tower structure. Therefore, the chosen approach is to calibrate fatigue design models with models which describe the damage evolution process in field, e.g. the fracture mechanics approach for metal and steel material. Concerning this approach, the aim is to find conceptual correlations with which a measured crack dimension from a unique structural hot spot can be used as a measure to define the already consumed service life at the relevant hot spots and consecutively the remaining useful service life of the whole structure. Thus, the next step of monitoring level 3 is to analyze possibilities of modelling the most relevant deterioration processes – in the scope of the dissertation fatigue processes – in a probabilistic domain.

4.6.4 STEEL FATIGUE PROCESS MODELING

Generally, fatigue arises at points of local stress concentrations, so-called hot spots represented by welds, cut-outs, and many mechanical connection types such as bolts. Due to inhomogeneities, welds are especially relevant as local hot spots and stress concentrations. State of the art engineering theory uses specific steel fatigue models for the description of the fatigue process caused by fluctuating stresses. Herein, the steel fatigue models are sub-divided into S-N models, based on experiments, and fracture mechanic models.

S-N models or curves are common empirical models relating the number of cycles to failure to different but constant stress ranges or amplitudes. In engineering theory there are different formulations of the S-N fatigue model, an overview is given by a state of the art review in Haibach (2006).

A classic formulation is represented by the Basquin equation, which describes a linear relationship between lnN_F and $ln\Delta S$.

$$N_F = C_1 \cdot \Delta S^{-m_1}$$

Equation 4-55

C_1 and m_1 are material parameters and are defined by experiments. Figure 4-55 displays a generic bi-linear S-N curve with cut off limit.

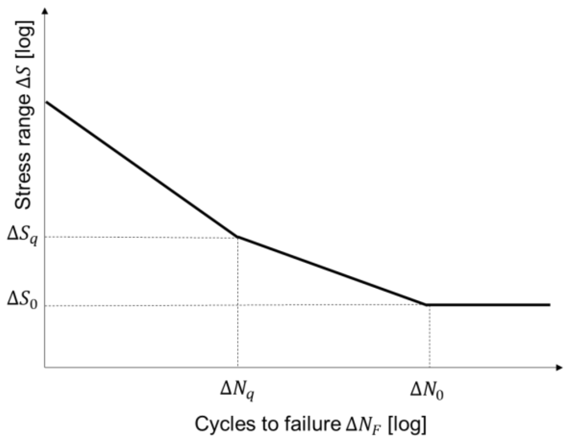


Figure 4-55: Generic representation of a bi-linear S-N-curve with cut off limit

One central aspect in the model is the cut-off fatigue threshold at the endurance limit ΔS_0. Below that threshold no fatigue failure will theoretically occur. Thus, three areas of the empirical fatigue design model can be defined:

$$N_F = C_1 \cdot \Delta S_1^{-m_1} \quad \Delta S \geq S_q$$

Equation 4-56

$$N_F = C_1 \cdot \Delta S_q^{(m_2 - m_1)} \cdot \Delta S^{-m_2} \quad \Delta S_q \geq \Delta S \geq \Delta S_0$$

Equation 4-57

$$N_F = \infty \quad \Delta S_0 \geq \Delta S$$

Equation 4-58

Three approaches to assessing the occurring material stresses in the S-N models are known, which essentially differ in how the material stresses are evaluated and compared – see Figure 4-56.

Nominal stress approach

S-N curves are given for specific types of details where S=S_N is the nominal stress. Nominal stresses are determined by external and internal loads and the cross-section properties of the specific structure (Haibach 2006).

Hot-spot-stress approach (also structural or geometric stress approach)

S-N curves are given for specific types of materials and environments (corrosive / non-corrosive) $S = S_{HS}$ is the hot spot stress. Stresses are evaluated by consideration of the local geometry. Weld effects are considered by extrapolating the stresses on the surface at some distance from the weld line (Haibach 2006).

Notch stress approach

Notch stresses are defined by $S = S_N$ and are the peak stresses at the root of a weld or the edge of a cut-out (Haibach 2006).

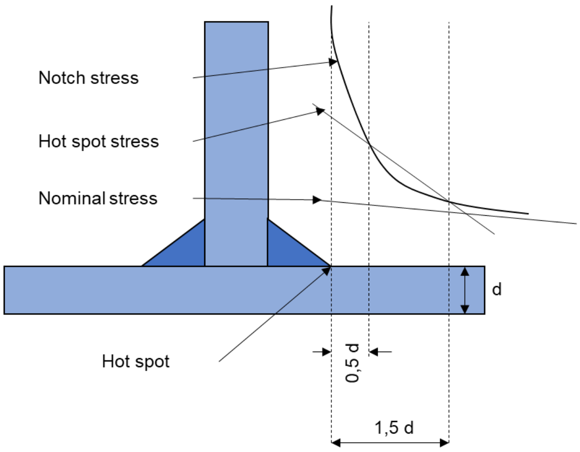


Figure 4-56: Different stress approaches in S-N fatigue analysis

The theory of linear damage accumulation goes back to Palmgren (1924). The Palmgren-Miner law assumes a linear and interaction-free damage accumulation. The damage accumulation after N cycles is independent of the order in which the stress cycles occur. The damage increment for each cycle has the stress range ΔS_i.

$$\Delta D_i = \frac{1}{N_{F,i}}$$

Equation 4-59

$N_{F,i}$ is the number of cycles to failure for ΔS_i as given by the associated S-N-curve. The total accumulated damage after N cycles can be described as follows:

$$D_{tot} = \sum_{i=1}^{N} \Delta D_i$$

Equation 4-60

Fatigue failure is reached when D_{tot} reaches a specific value, here expressed as D_{max}. Generally D_{max} is modelled with the mean value 1.

Subsequently, the S-N fatigue limit state function can be described:

$$g_{SN} = D_{max} - D_{tot}$$

Equation 4-61

The stress process is described by the distribution of stress ranges $f_{\Delta S}(\Delta S)$, the stress cycle rate ν and the mean stress ratio R_S.

The stress ranges and number of stress cycles are normally application specific. Considering the distribution, those two parameters can often be approximated by a Weibull or Rayleigh distribution approach. Often the Weibull distribution is a good description for natural processes related to dynamic response of elastic system – e.g. marine structures or wind turbines.

Considering a reasonable counting algorithm, the *Rainflow* counting process has proven to suit best for cyclic loading. A profound description of fatigue damage quantifying methods can be found in Haibach (2006).

Due to the cumulative nature of the Palmgren-Miner law for high cycle fatigue, the stress range distribution can be replaced by the expected value of the m_1^{th} order of the stress range $E[\Delta S^{m_1}]$. If the material parameters C_1 and m_1 are considered constant with time, the total damage in the time period T can be defined as:

$$D_{tot}(T) = \sum_{i=1}^{N(T)} \Delta D_i \approx N(T) \cdot E[\Delta D_i] = N(T) \cdot \frac{1}{C_i} \cdot E[\Delta S^{m_1}]$$

Equation 4-62

This relationship is only valid for single slope S-N curves. If the stress range is distributed according to Weibull, the model is described by only two parameters and an analytical solution is given.

For the case of a simple one-slope S-N diagram with the parameters C_1 and m_1 the induced damage is:

$$E[\Delta D_i] = \frac{1}{C_1} {k_{\Delta S}}^{m_1} \Gamma(1 + \frac{m_1}{a_{\Delta S}})$$

Equation 4-63

With $k_{\Delta S}$ as scale parameter and $a_{\Delta S}$ as shape parameter.

For the case of a S-N curve with cut-off the damage increment is:

$$E[\Delta D_i] = \frac{1}{C_1} {k_{\Delta S}}^{m_1} \Gamma(1 + \frac{m_1}{\lambda_{\Delta S}}, (\frac{\Delta S_0}{k_{\Delta S}})^{\lambda_{\Delta S}})$$

Equation 4-64

For the most common case, with a two-slope S-N curve without cut-off the relationship is:

$$E[\Delta D_i] = \frac{1}{C_1} {k_{\Delta S}}^{m_1} \Gamma(1 + \frac{m_1}{\lambda_{\Delta S}}, \left(\frac{\Delta S_0}{k_{\Delta S}}\right)^{\lambda_{\Delta S}} + \frac{k_{\Delta S}^{m_1}}{C_1} \Delta S_q^{m_1 - m_2} [\Gamma\left(1 + \frac{m_2}{\lambda_{\Delta S}}, \left(\frac{\Delta S_0}{k_{\Delta S}}\right)^{\lambda_{\Delta S}}\right) - \Gamma\left(1 + \frac{m_2}{\lambda_{\Delta S}}, \left(\frac{\Delta S_q}{k_{\Delta S}}\right)^{\lambda_{\Delta S}}\right)]$$

Equation 4-65

S and N can be related as follows:

- $\Delta S_q = (C_1/N_q)^{1/m_1}$
- $\Delta S_0 = (C_1/N_0)^{1/m_1}$ 1 slope with cut off
- $\Delta S_0 = (C_1 \Delta S_q{}^{(m_2-m_1)}/N_0)^{1/m_2}$ 2 slope with cut off

The number of stress cycles in a time interval T is: $N(T) = \nu \cdot T$ (stress cycle rate [Hz] x T [s])

Generally, the described empirical fatigue design laws and models inherit many uncertainties. The three general uncertainties in the empirical fatigue design approach are:

- Uncertainty of the fatigue model (S-N curve)
- Uncertainty of the fatigue resistance (uncertainty on the applied S-N curve)
- Uncertainty on the loading/sensors

The applicable limit state function for the fatigue design state of a steel structure can be expressed as follows:

$$g_{SN} = \Delta - \nu T E[\Delta D_i]$$

$E[\Delta D_i]$ for Weibull-distributed loading of structure

Equation 4-66

The fracture mechanic approach is opposed to the S-N model approach. The theory implies the initiation and gradual development and propagation of small cracks in the microstructure due to cyclic loads. In practice, the crack propagation mechanism is often combined with corrosion mechanisms. The fracture mechanic fatigue models introduce a stress intensity factor, which describes the crack propagation in the models. Fatigue crack growth models are mainly based on the linear elastic fracture mechanic theory (Anderson 2005).

The evolution or life time of a crack can be divided in three stages (Figure 4-57):

- Initiation → Number of cycles spent in that phase → N_I
- Propagation → Number of cycles spent in that phase → N_P
- Failure → Total number of cycles N_F → analogous to the S-N approach

$$N_F = N_I + N_P$$

Equation 4-67

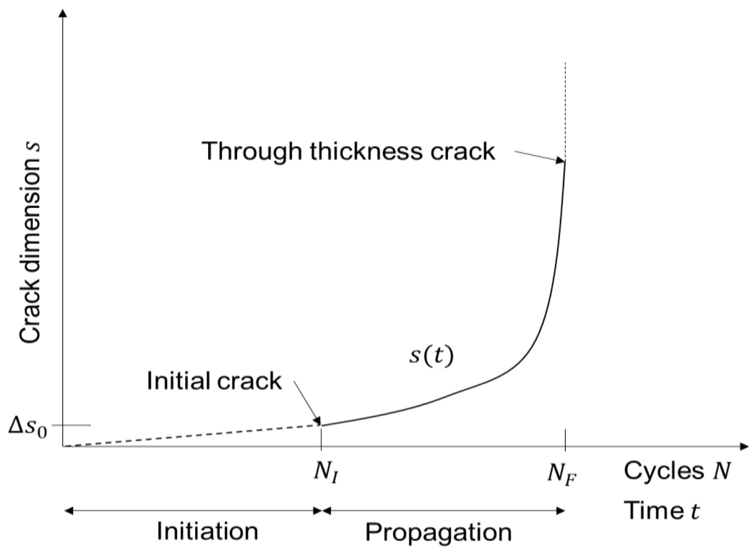


Figure 4-57: Generic crack propagation phases and fatigue failure – adapted from (Straub 2004)

For the purpose of deterioration control, a suitable concept can be to combine the S-N model approach with the fracture mechanics approach to a hybrid probabilistic model, which will be able to describe the fatigue crack dimension at any time during the service life of a wind turbine.

For deterioration control, a suitable concept is combining the S-N model with the fracture mechanics approach to a hybrid probabilistic model, which can describe the fatigue crack dimension at any time during the service life of a wind turbine.

The S-N model considers all design assumptions which have been made to design the structural element resistant to fatigue damage. On the other hand, the fracture mechanics approach is suitable for in-service deterioration control of structural elements; crack width and crack length can be measured by nondestructive testing methods e.g. ultrasound.

In every model calibration, the quality of said calibration must always be evaluated. The S-N model gives information on whether a hot spot has failed or survived, whereas the FM model gives the crack dimension after any number of cycles. Therefore, the FM model must be calibrated in line with the S-N model such that after the number of cycles to failure is attained, the critical crack size is reached in the FM model. Figure 4-58 displays the aimed model calibration of S-N and FM model graphically.

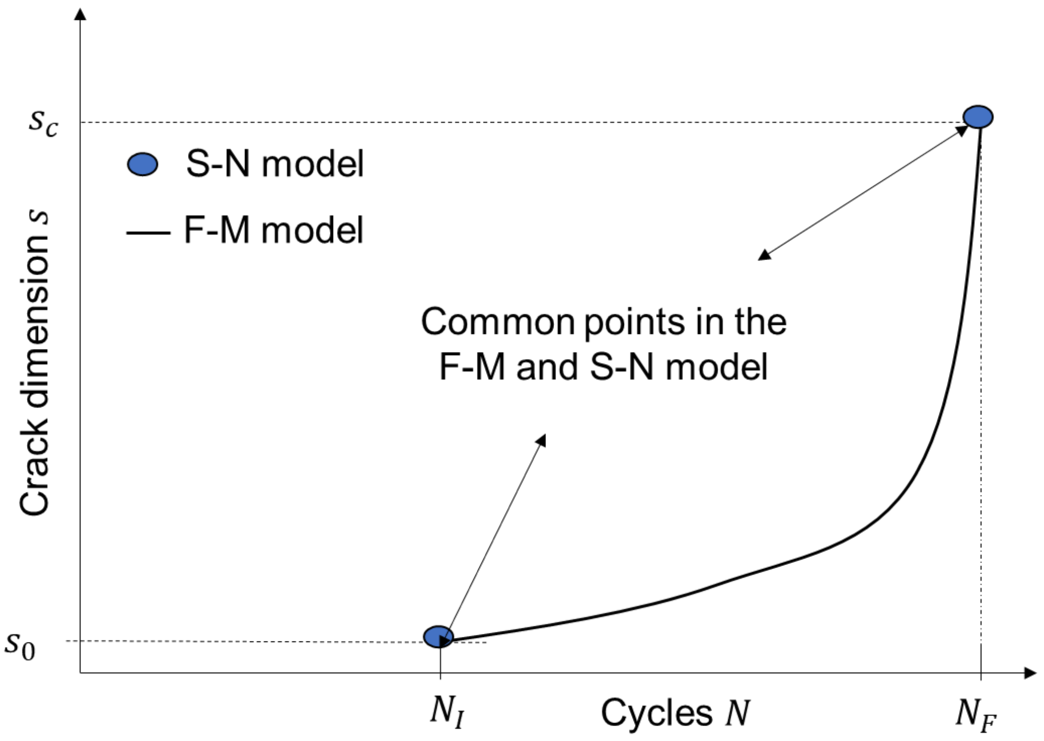


Figure 4-58: Fatigue model calibration of S-N and FM model – adapted from (Straub 2004)

A stochastic description of the fatigue evolution process is more realistic and fitting for wind-induced loading. The parameters to which the model should be fitted are random. In engineering theory, several calibration algorithms have already been developed (Straub 2004; Ziegler and Muskulus 2016a; Ziegler and Muskulus 2016b).

Straub developed a hybrid solution for a calibration of the S-N model to the FM model. The probability distribution of $F_{N_F}(N)$ is equivalent to the probability of failure p_f as a function of the number of cycles.

$$p_F(N) = F_{N_F}(N)$$

Equation 4-68

The actual calibration is performed by a least-square fitting in β-space.

$$\beta = -\Phi^{-1}(p_f)$$

Equation 4-69

A minimization with respect to the parameters of the fracture mechanics model $x_1 \dots x_N$ is carried out.

$$\min_{x_1 \dots x_N} \sum_{t=1}^{T_{SL}} (\beta_{SN}(t) - \beta_{FM}(t; x_1 \dots x_N))^2$$

With:

- $\beta_{SN}(t)$ as the reliability at time t using the S-N model
- $\beta_{FM}(t; x_1 \dots x_N)$ as the reliability at time t using FM model

Equation 4-70

The evaluation of reliability indexes is performed by a FORM or SORM algorithm (RCP & ERACONS 2017). The choice of parameters to be calibrated depends on the applied FM model. Generally, two parameters must be calibrated. A first crack growth rate parameter is essential for its high influence on crack growth. The second parameter chosen influences structural reliability, however, little information is available for the latter. Figure 4-59 displays a generic calibration result of the S-N model to the FM model.

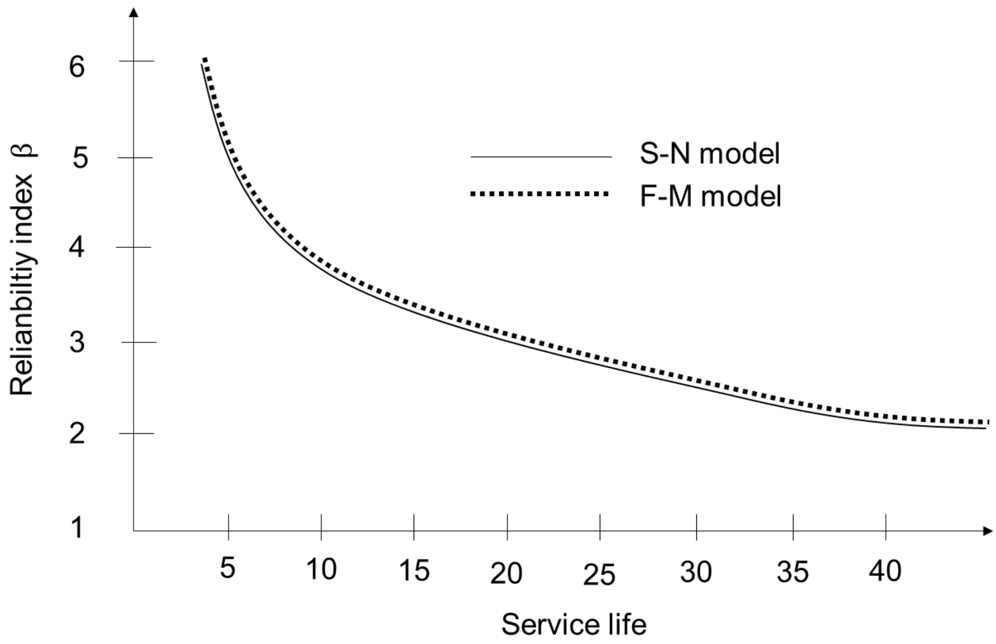


Figure 4-59: Calibration of S-N model to FM model – adapted from (Straub 2004)

The choice of calibrated crack growth model is crucial to the practicability of the described approach. Therefore, it must be analyzed which model delivers the most realistic values and which model is more conservative. Furthermore, the parameters subject to calibration must be discussed as well. Straub analyzed three different FM models for calibration to the S-N model. Influence of crack initiation processes are neglected; the initiation time is assumed to be $N_i = 0$. Also, the initial crack geometry is assumed the same for all models under investigation. Due to practicability reasons the simple one-dimensional Paris law crack growth model is suitable.

The simple one-dimensional Paris-law can be expressed as follows:

$$\frac{d_a}{d_N} = C_p \Delta K^{m_{fm}}$$

With $a \geq a_0$ and $K < K_{IC}$

Equation 4-71

The crack depth is obtained by integration of the equation over all applied stress cycles. The boundary conditions are given by the number of cycles to crack initiation N_I and the corresponding initial crack size a_0.

$$a(N_I) = a_0$$

Equation 4-72

The stress intensity factor K can be obtained from linear elastic fracture mechanics – relevant codes, parametric approximation, or an FE-analysis of the relevant structural element. K is a function of a and a/d. A general model is described in Madsen et al. (2006):

$$K = Y_G(a)S\sqrt{\pi a}$$

Equation 4-73

$Y_G(a)$ is a geometry factor accounting for the crack size and considers geometrical boundary conditions; it is normally obtained from experiments. It is possible to derive a one-dimensional $Y_G(a)$ using an assumed depth-to-length- ratio a/c.

The one-dimensional crack growth model is evaluated by separation and integration of the variables:

$$C_P \cdot \Delta S^{m_{fm}} \cdot (N - N_I) = \int_{a_0}^{a} \frac{dz}{Y_G(z)^{m_{fm}}(z \cdot \pi)^{m_{FM}}}$$

Equation 4-74

Solving the equation with respect to a, the crack depth after N cycles is obtained.

$$\boldsymbol{a(N) = (a_0^{(2-m_{f_m})/2} + \frac{2 - m_{f_m}}{2} C_P\left(Y_G\pi^{1/2}\Delta S\right)^{m_{f_m}}(N - N_I))^{2/(2-m_{f_m})}, m_{f_m} \neq 2}$$

Equation 4-75

Conceptually, Equation 4-75 enables the use of crack information from in-field inspections to determine the actual number of cycles the respective structural hot spots have seen as a method of estimating existing material resistance reserves at that hot spot. This correlation is the basis for operating wind turbine structures in a damage tolerant service life beyond the originally designed service life. Since more and more wind turbine supporting structure designs are built in reinforced concrete design, it is also necessary to investigate approaches on applying the described inspection update for concrete parts in the supporting structure system as well. Additionally, it must be clarified which concepts are suitable for defining optimal inspection intervals in the damage tolerant phase of the tower, balancing a minimum reliability and safety standard with induced inspection cost.

4.6.5 CONCRETE FATIGUE PROCESS MODELLING

Reinforced concrete as used in supporting structures of wind turbines is a composite material in which the concrete part covers compressive stresses and reinforcement parts cover for tensile stresses. Cracks in reinforced concrete are not avoidable. The reinforcement in concrete is nonstressed and made to carry the tensile stresses. Concrete has a considerably low tensile strength of about 2 to 3 N/mm². It is only by volitional and controlled cracks that structural forces can be transferred to the reinforcement. Thus, the reinforcement in concrete structures can only work efficiently, if the concrete is cracked. However, the distribution and limitation of cracks in concrete structures need to be monitored and controlled to guarantee structural integrity and to prevent intrusion of damaging substances. If this is not the case, the service life and stability – e.g. load bearing capacity – of concrete structures are compromised. Further instability is caused by corrosive and concrete-degrading substances entering the concrete component.

First and foremost, thermal and plastic shrinkage cracks during the production phase or in early years can be categorized as normal cracks. The operating environment of the concrete structure will cause cracks in combination with drying and shrinkage processes in later years. Other than this, structural cracks caused by static and or dynamic overloading which leads to high local stress concentrations or creep around structural details can be observed.

Figure 4-60 summarizes the basic root causes of concrete cracking.

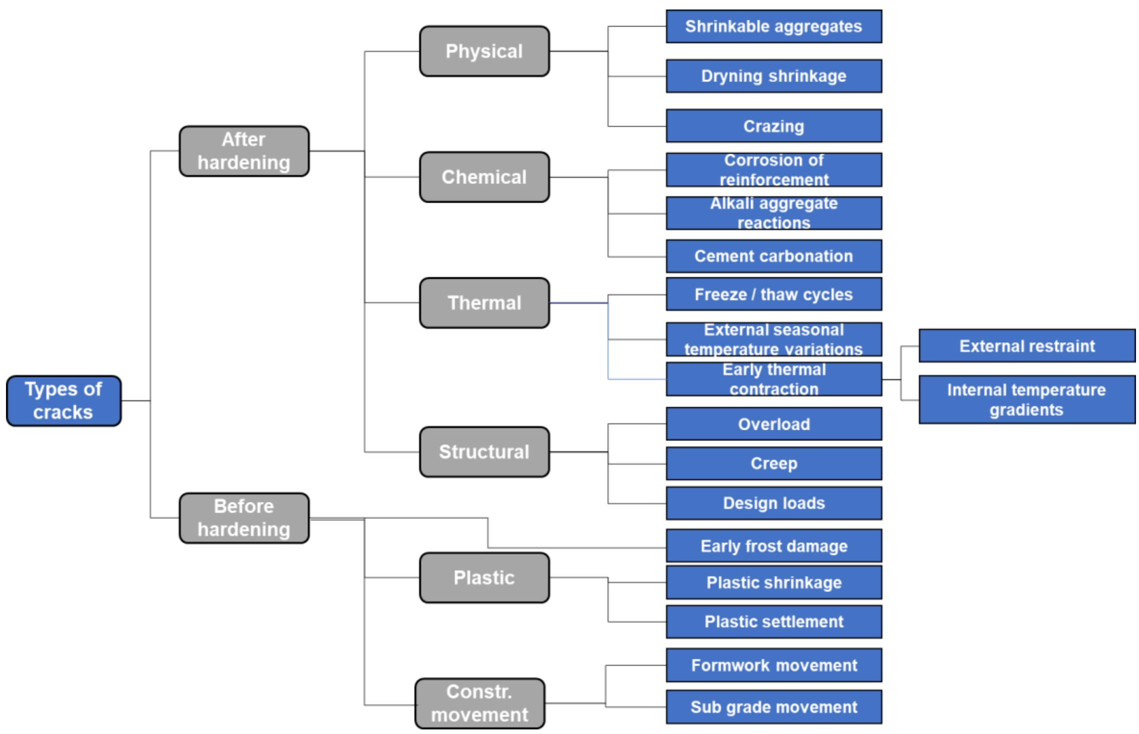


Figure 4-60: Basic root causes of concrete cracking – adapted from (Bosold and Grünewald 2014)

Other non-structural crack causes are insufficient concrete covering and improperly installed concrete reinforcement. Further site-specific root causes are concreting at low temperatures, incorrect concrete mix or water at site. Fatigue can be described as the process of repetitive stress below the material strength, causing a gradual process of wear, leading to a fatigue crack or failure. For concrete, the fatigue process is subdivided into three phases:

1) Crack initiation
2) Crack growth
3) Critical unstable crack growth

With increasing stress, micro cracks grow in the concrete. Further stressing leads to the unification and expansion of cracks. Macro and matrix cracks develop and finally build up to fractured surfaces and the final fatigue failure of a cross section. Fibers added to the concrete normally enhance the stress resistance capabilities of a concrete component in general. With progressing damage evolution and crack growth of the concrete parts, the fibers overtake load transferring capability of the concrete parts, making the concrete component more durable. However, the addition of fibers can be contra-productive if the compression phase in the component fabrication is not sufficient or the type of fibers do not match the type of concrete used. Pore formation is the consequence, leading to premature crack initiation and a low fatigue strength of the component (Thiele 2016).

Characterizing parameters of cyclic loading of concrete components are:

- Maximum and minimum stress
- Loading type
    - Centric
    - Ex-centric
    - Uni-axial
    - Multi-axial
- Loading frequency
- Ambient conditions
    - Moist
    - Dry

Figure 4-61 displays the normalization of the specific loads used in concrete fatigue analysis, the stresses are normalized with the static compressive strength of the concrete. Thus, it is possible to compare concrete with different compressive strength characteristics.

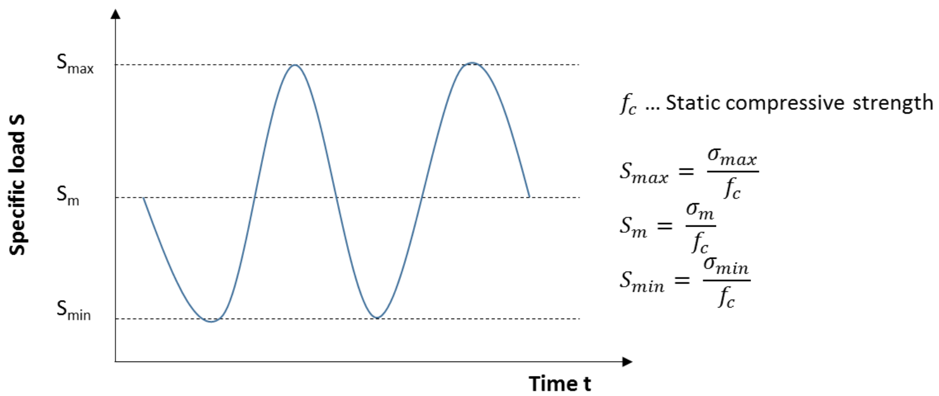


Figure 4-61: Normalization of specific loads for concrete structure fatigue analysis

As opposed to metal materials, concrete components show no ultimate fatigue strength. Furthermore, concrete is only weakly dependent on the loading character – static or dynamic. When it comes to its fatigue resistance, concrete shows nearly the same behavior for both static or dynamic load cases. Bi-linear S-N laws for concrete were first described by Hsu (1981) and Aas-Jakobsen (1970). However, in engineering theory there is a lack of descriptive models for the concrete damage evolution process. An interplay with other deterioration mechanisms such as corrosion must often be considered. Figure 4-62 depicts a generic model using the bi-linear S-N law versus the theoretical damage evolution process of concrete.

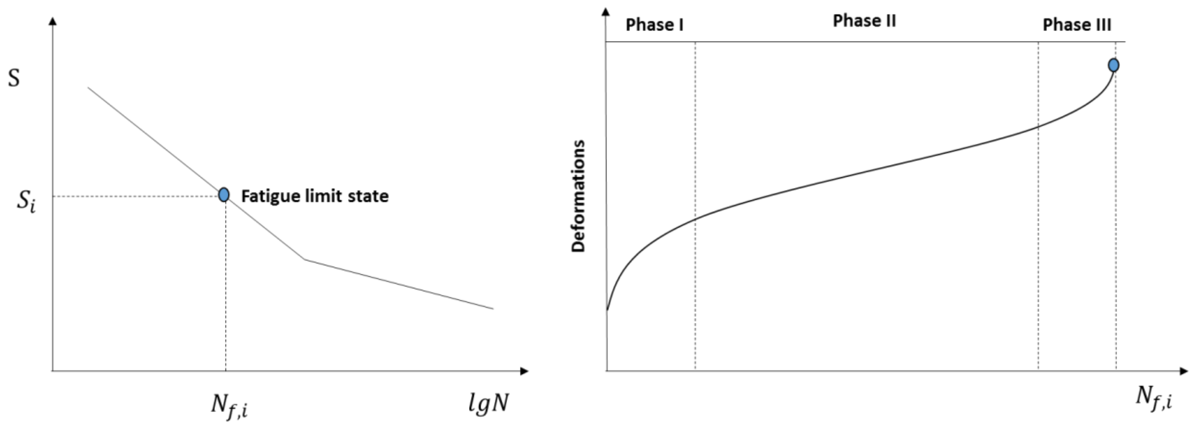


Figure 4-62: Bi-linear S-N law and damage evolution process of concrete

The tensile strength behavior of concrete is brittle. The compressive strength behavior of concrete is ductile. For up to ca. 30-40 % of the compressive strength, concrete shows a linear-elastic behavior. From this threshold until the fatigue limit state is reached, the deformation behavior is non-linear to exponential. In the linear behavior range, the micro cracks created during the hydration phase open. Then in the non-linear damage evolution range the present crack structures grow further and cause irreversible microstructural changes resulting in plastic deformations. Thus, material strength of the concrete element is lowered.

The shape of the stress-strain curve of the concrete material is mainly dependent on the compressive strength. Ultra-high-performance-concrete (UHPC) can reach up to 250 N / mm² compressive strength. Higher material strength results in a more distinct elastic material behavior before it comes to a material fracture. Also, UHPC reaches a higher fracture strain than normal concrete.

Multi-axial loading enhances the ductility of concrete, because micro crack formation is hindered. Much research has been conducted on fatigue of concrete. A summary of the most relevant publications is given in Thiele (2016). Currently valid codes and regulations consider fatigue of concrete structures, however, miss important aspects like the estimation of remaining useful service life reserves of a concrete structure (CEB-FIP 1993, DIN-EN 1992-2 2010, DIN EN 1992-1-1 2011, CEB FIP 2012).

Figure 4-63 displays the fatigue cycle number categorizations for concrete structures and classifies the high cycle loading of wind turbine structures compared to other structures in field under high cycle fatigue (Gasch et al. 2007; Hau 2006; Burton et al. 2011; Loraux 2017).

For example: If the rotor system of a wind turbine is operating with 15 revolutions per minute at rated speed, one can apply the following estimation for the magnitude of load cycle amounts for the designed service life of 20 years - only for the rotational 1p excitation of the rotor system:

900 revolutions per hour x 6,000 operating hours per year x 20 years = 1.08 x 10^8 load cycles

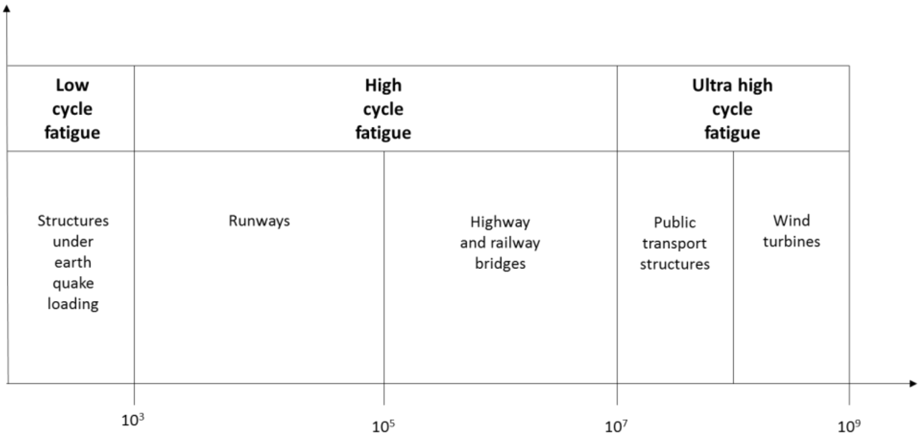


Figure 4-63: Cycle number categories for concrete structures – adopted from (Thiele 2016)

Generally, the fatigue strength of materials underlies considerable statistic variances. For a reliable statistic basis, a high number of fatigue tests is necessary. Especially the compressive strength of the specific concrete element is subject to scatter. So far, the existence of an ultimate fatigue strength for concrete could not be proved. A theoretical discussion of ultimate fatigue strength is presented in Weigler and Freitag (1975) and Petryna (2004) and should range between 10^{10} and 10^{11} load cycles.

Figure 4-64 displays the different fatigue behavior of concrete and fatigue in comparison.

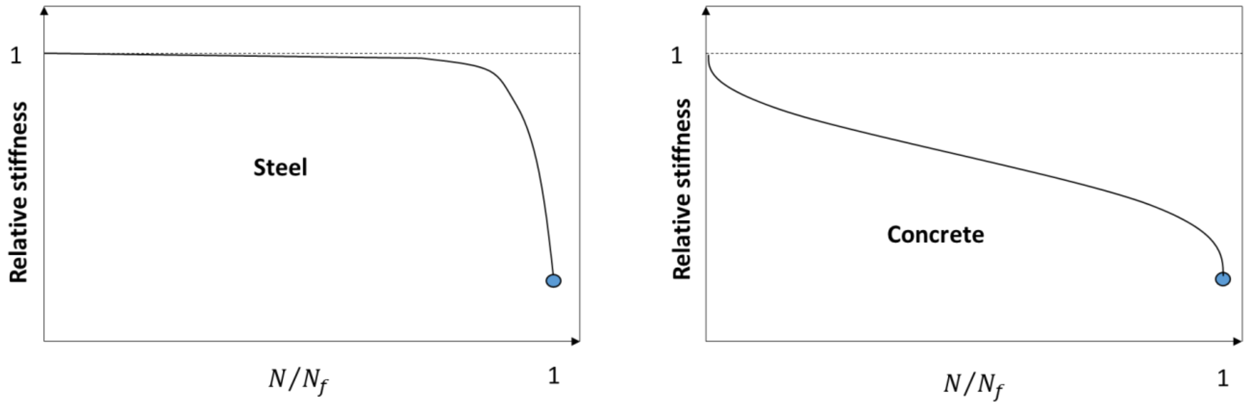


Figure 4-64: Different fatigue behavior of steel and concrete parts in comparison

Parameters influencing the damage evolution process of concrete are, first and foremost stress and external parameters:

- Load level (intermediate load and amplitude)
- Load frequency
- Type of loading (tensile, compressive or alternating load)
- Resting times
- Load history / sequence
- Concrete humidity
- Concrete temperature

Material parameters also influence the damage evolution process directly:

- Static material strength
- Stiffness
- Composition (aggregates, grading curve, cement ratio, air pores)

The behavior of reinforced concrete was intensively studied by Petryna (2004).

The fatigue evolution process of concrete material is significantly different from the fatigue process of metal or steel structures. The main reason is the heterogeneous microstructure and the interaction of microstructural parts in structural elements made from concrete.

Phase 0 – Initial State

The manufacturing process of the concrete element creates a microstructure with air, gel, and capillary pores in the cement stone. Additionally, the aggregates are normally pre-fractured. Disoriented micro cracks exist in the cement stone and in the contact zone. Due to the hydration process and the shrinkage, the cement stone inherits residual stresses, displayed as dis-oriented tensile stresses.

Phase I – Balancing Phase

This phase is characterized by the effects caused by the first application of compressive loading. The still inhomogeneous microstructure causes inhomogeneous stress and strain distributions in the structure, thus creating a broad spectrum of local stress concentrations causing different stress levels on the microstructural level. The local stresses develop in all directions in space, inducing multi-axial stress conditions inside the structure. Application of the initial stressing activates all time-independent plastic deformation processes in the material structure. Therefore, even low external loads can cause transgression of local load-bearing capacities resulting in damages and plastic deformation on the microstructural level inside the structure – external crack growth is not ascertainable in that phase. The internal crack and deformation processes result in high acoustic emission activities in that phase.

At the end of phase I, a continuous fatigue evolution process begins. The settlement of present crack structures in the cement stone cause sudden stiffness in the upper range of the E-modulus.

Phase II – Constant Phase

Phase II is characterized by a continuous increase of the overall deformation. Loosening and reduction of stiffness accompany the evolution process, whereas the stiffness in the upper range of the stress area and the compressive strength remain stable. Reason here fore, as is the case in phase I, are viscous transformations in the cement stone which go along with local loosening. At this point, there is still no distinctive external crack growth visible.

Phase III – Instable Phase

In phase III, the fatigue evolution process enters the instable section. The linear developments of loosening and overall plastic deformation undergo a non-linear development. Reduction of stiffness in the upper stress area begins and goes along with a reduction of the compressive strength. Sound emission activities tend to undergo an exponential increase due to considerable increase of cracking mechanisms in the structure. Vertical orientation of the cracks is predominant. However, fatigue failure is not characterized by an abrupt crack through the entire thickness. Microstructural cracking starts slowly and develops exponentially towards the end of phase III. Microstructural cracks unite, leading to less microstructural elements contributing to the load transferring process. In turn, the applied loads exceed the load-bearing capacities of the intact microstructural areas, which results in further plastic damages and cracks in the microstructure. Eventually the micro cracks grow to become macro cracks, even further unification leads to a fractured surface and a final fatigue damage of the structural element. Figure 4-65 describes the damage evolution process of concrete graphically.

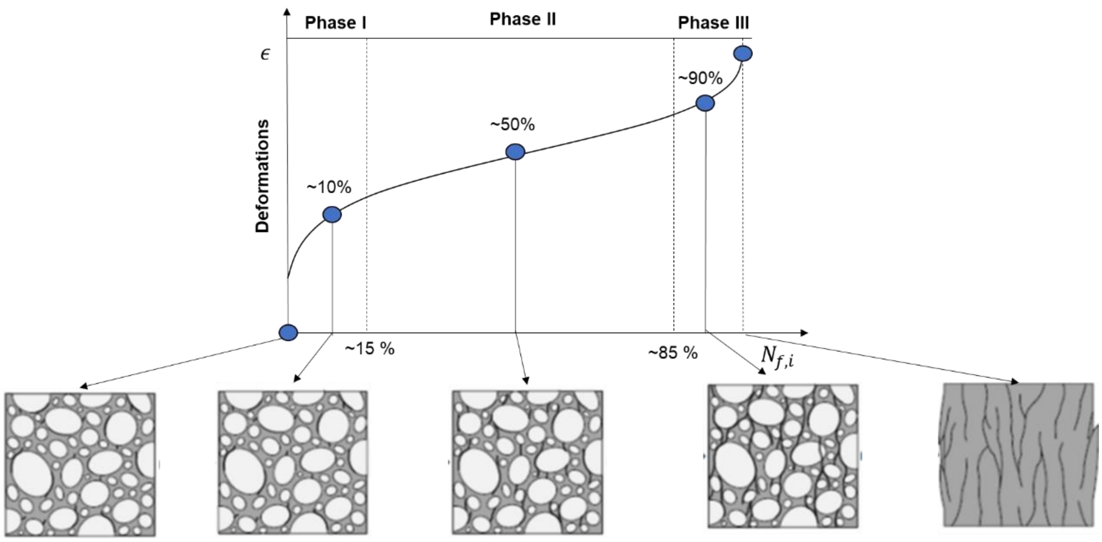


Figure 4-65: Damage evolution process of concrete – adapted from (Thiele 2016)

Thiele developed a mathematical approach to model the fatigue deterioration process of concrete. The s-shaped damage evolution process can be described by a broken rational function (Thiele 2016):

$$f(x) = C_1 + \frac{C_2}{x + C_3} + \frac{C_4}{x + C_5}$$

Equation 4-76

Thiele analyzed suitable fatigue performance and damage indicators for concrete elements showing that the E-Modulus qualifies as a fatigue performance indicator for concrete structures. Besides the E-Modulus, deformations, cycle counts, and micro cracks were also found to be suitable as potential fatigue performance indicators. Resulting from an analysis of ultrasound measurements as such, ultrasound amplitudes showed a high sensitivity to damage in the concrete specimen. Ultrasound velocities in the specimen showed to be sensitive to damage evolution. In both cases scattering in the measurement campaign was relatively low compared to other measurement principles, e.g. sound emission measurements. An advantage of ultrasound measurements as an in-service inspection technique is that measurements can be carried out on the structural element in service without a special load slope or other preparations. However, it must be assured that the coupling of the ultrasound sensors is appropriate. A suitable index for the quality of fatigue performance indicators for the damage evolution process of concrete is the scatter behavior over the evolution process of the relevant indicator. The scatter intensity can be evaluated in a quality index FPI_{QI}, dividing the standard deviation s_x by the mean value $\bar{x}$.

$$FPI_{QI} = \frac{s_x}{\bar{x}}$$

Equation 4-77

Figure 4-66 expresses the context of the damage evolution process of concrete and the FPI graphically.

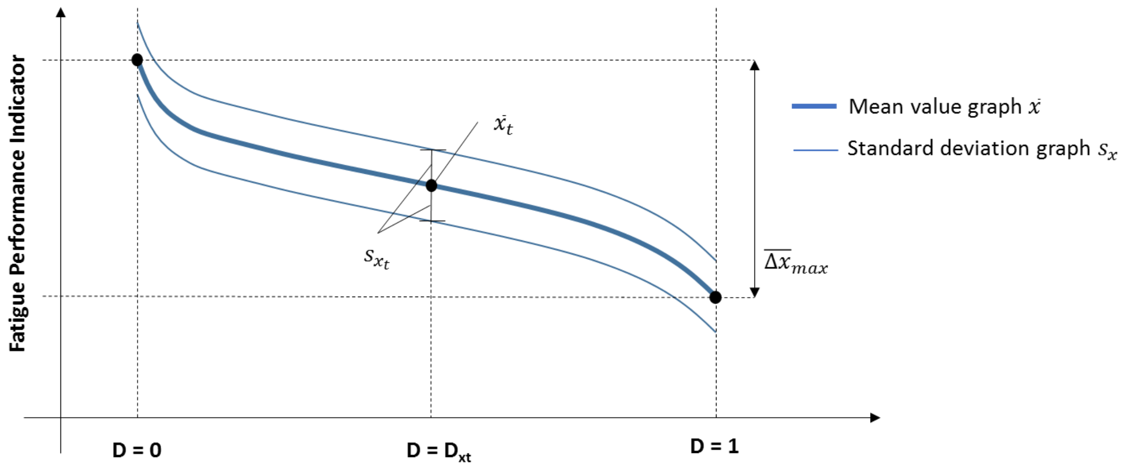


Figure 4-66: Fatigue Performance Indicator (FPI) of concrete damage evolution process – adapted from (Thiele 2016)

The damage evolution model for ultrasound measurements showed the best results, the following fitting parameters were retrieved for ultrasound damage tracking (Thiele 2016).

Table 4-7: Fitting paraments for fatigue damage tracking with ultrasound measurements (Thiele 2016)

	C_1	C_2	C_3	C_4	C_5
US $v_{f,0}$	83.6	147.4	8.6	450.3	-115.4
US $v_{f,max}$	88.4	216	16.6	286.5	-109.2
US $A_{f,0}$	253.6	159.4	3.9	92.346	-470
US $A_{f,max}$	142.7	533.6	14.1	2077	-245

Thus, applying ultrasound-based nondestructive testing techniques – primarily in transmission mode – and tracking the alteration of ultrasound velocities as well as the reduction of amplitudes can be a practical approach to monitor the damage evolution of concrete parts in field and correlate the inspection information to design fatigue models, in order to evaluate the actual consumed resistance reserves, applying the probabilistic concepts described in chapter 4.6.3.

4.6.6 DECISION ANALYSIS

Ultimately, the decision analysis process aims for the identification of optimal decisions on maintenance actions for deteriorating structures. The decision environment is subjected to uncertainty under the following aspects:

- Uncertainty on the state of the system; state of deterioration
- Uncertainty on the performance of the inspection; probability of detection (POD)
- Uncertainty on the performance of repair actions
- Uncertainty on the consequences of failures

The decision problem is summarized in a decision tree. Each path of the decision tree is assigned a utility value and its probability characteristics. Considering the point in time and informational characteristics of the decision problem, three basic situations can be defined.

The first situation refers to the prior analysis which is conducted with given information. Here, the utility function and the probabilities of the various states of nature corresponding to the different consequences have been defined. The decision analysis is reduced to the computation of the expected utilities and finding the optimal point of the optimization problem.

The second situation, the posterior analysis, refers to a decision analysis problem with additional information on the state of nature. If additional information becomes available – e.g. through inspections – the probability structure in the decision problem is updated. The probability update is carried out using Bayes' rule.

Lastly, the pre-posterior analysis is a decision analysis problem dealing with unknown information. The decision maker has the possibility to buy additional information through an experiment. If the cost of this information is small in comparison to the potential value of information, the experiment should be performed. If several experiments are potentially suitable, the decision maker must choose the experiment yielding the overall largest utility for his decision problem.

The utility theory – as well as the Bayesian theory - is a corner stone of the classical decision theory. The basic principles were developed by Neumann and Morgenstern (1947); Raiffa and Schlaifer (2000).

As a first step, a set of possible events is defined, $E_1$to E_n. These events are compared with different outcomes of a game. Events with a large index are preferred over other events with a lower index. The decision maker can choose different actions also called lotteries. Each action will lead to probabilities of occurrence for different events. E.g. action a will lead to Event E_1 with the probability $p_1^{(a)}$ and to Event E_2 with the probability $p_2^{(a)}$. Action b will lead to event E_1 with the probability $p_1^{(b)}$ and so forth.

All probabilities of occurrence fulfill the basic condition: $p_1^i + p_2^i + p_n^i = 1$

Equation 4-78

The utility index is used to express specific preferences of the decision maker in such a way that one decision is preferred over another, if the expected utility of the former is larger than the utility of the latter. A utility index u_D can be assigned to the different basic events $E_1$to E_n.

The final optimization criterion is the expected cost criterion. Therefore, the utility index u_D is assigned to monetary units in a linear way for the considered range of events. The indirect costs associated with the events of failure, repair, and inspection are included in the probabilistic modelling. Thus, all consequences of an event must be expressed in monetary terms, this is considered a weakness of the theory, because monetary values are not always publicly available. Straub (2004) developed a generic decision procedure for such problems:

A simple application scenario of this theory can be found when action a_D is to be planned, all relevant information on the true state Θ is available, and it is not possible to learn more on Θ before a_D is performed.

The true state is described by a prior probability density function $f'_\Theta\theta$. Prior decision analysis aims at identifying the action a_D that maximizes the expected utility $E[u_D]$, whereby the utility is expressed as a function of a_D and Θ.

$$max_a u_D(a_D) = max_{a_D} E_\Theta[u_D(a_D,\theta)] = max_{a_D} \int_\Theta^\infty u_D(a_D,\theta)\, f'_\Theta \theta d\theta$$

Equation 4-79

The posterior decision analysis is principally identical to the prior decision analysis, except that new information – e.g. from inspections – is considered for the decision optimization - Figure 4-67. Based on the additional information the prior probability density function is updated to the posterior probability density function f''_Θ. The equation for applying the Bayes' rule to update the probability density function based on the event E_1 is defined as follows:

$$f''_x(x|E_1) = L(E_1|x) \cdot f'_x \cdot const$$

Whereby:

- f''_x … posterior pdf of x
- f'_x … prior pdf of x

Equation 4-80

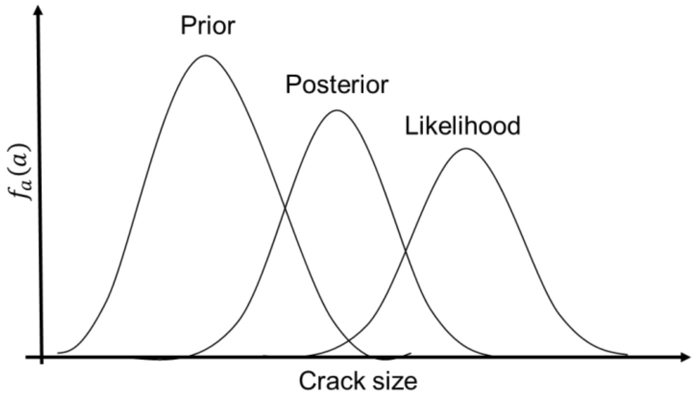


Figure 4-67: Prior, posterior and likelihood probability density function

The pre-posterior decision analysis aims at identifying the optimal decision on possible inspection actions to enable optimal maintenance planning. Therefore, the following decision parameters and events must be considered:

- e = inspections or experiments; number, time, location and type of inspections
- Z = inspection outcomes: no detections, detections, observed crack length and depth
- a_D = actions after inspections → operate, repair, change of inspection or maintenance strategy
- Θ = true but unknown state of nature → non-failure, failure, degree of deterioration
- $u_D(e, Z, a, \theta)$ = utility assigned by consideration of the preferences of the decision maker to any combinations of the given decisions and events → expressed in monetary terms

In the pre-posterior decision analysis, it is possible to determine the expected utility resulting from the inspection decision a_D by assigning a decision rule d_D to the inspection result z, which determines future actions in regard to maintenance activities and inspection plans.

$$a = d_D(e, z)$$

Equation 4-81

Thus, an inspection and maintenance strategy is defined by a set of the variables e and d_D. The corresponding expected utility is defined as:

$$E[u_D(e.d_D)] = E_{\Theta,\mathrm{Z|e}.d_D}[u_D(e, Z, d_D(e, Z), \Theta)]$$

Equation 4-82

The optimal inspection strategy is obtained by maximizing Equation 4-82, wherein u_D is a deterministic function. All random variables that are not included in either Z or θ are integrated for the determination of u_D.

Straub shows an example for the clarification of this concept (Straub 2004):

Any weld is susceptible to initial cracks which are quantified by their size Θ, corresponding to the uncertain state of nature. If the maximal depth of the crack exceeds a certain value θ_R, it is economical to repair the weld; this action is denoted $a_{d,1}$. A priori, the weld would not be repaired, an action denoted by $a_{d,0}$. Assuming perfect information on θ were known, the optimal action could be chosen:

$$v_t(\theta) = \max[0, u_{d,t}, \left(a_{d,1}, \theta\right) - u_t(a_{d,0}, \theta)]$$

$v_t(\theta)$ … conditional value of perfect information

Equation 4-83

If performing a perfect initial inspection were possible, it would be conceivable to define the inspection crack size with certainty. The expected value of information gained by the inspection can be expressed as follows:

$$EVPI = E_{\Theta}[CVPI(\theta)] = \int_{\Theta} v_t(\theta) f'_{\Theta}(\theta) d\theta$$

Equation 4-84

However, an inspection e can only provide imperfect information. Therefore, likelihood models can model the uncertainty in the inspection results:

$$L(z|e, \theta)$$

Equation 4-85

Based on the inspection results and the likelihood, the prior probability density function of Θ is updated to the posterior probability density function $f''_{\Theta}(\Theta|z)$.

Then, by optimal posterior decision analysis, the optimal maintenance activities can be evaluated as a function of the inspection outcome z. The expected utilities are evaluated as follows:

$$E''_{\Theta|z}\left[u_{d,t}\left(a_{d,t}, \theta\right)\right] = \int_{\Theta} u_{d,t}(a_{d,i}, \theta) f''_{\Theta}(\theta|z) d\theta\, ; i = 1{,}2$$

Equation 4-86

$E''_{\Theta|z}$ denotes the expectation with respect to the posterior probability density function of Θ. If the optimal action – given outcome z - is $a_{d,0}$, which is equal to the optimal action before the inspection, then the inspection does not alter the terminal utility and has therefore no value. If, however the optimal action given outcome z is $a_{d,1}$, then the inspection has a value which is equal to the difference in the expected utility. The information obtained by the inspection can be expressed as follows:

$$v_{tz}(z) = \max[0, E''_{\Theta|z}\left[u_{d,t}\left(a_{d,1}, \theta\right)\right] - E''_{\Theta|z}[u_{d,t}(a_{d,0}, \theta)]]$$

Equation 4-87

Whereby $\upsilon_{tz}(z)$ is defined as conditional value of the sample information regarding the inspection outcome z. Based on the prior probability density function of Θ and the inspection model, the probability of occurrence of the possible inspection outcomes can be evaluated:

$$f_z(z|e) = E_\Theta[f_z(z|e,\theta)] = \int_\Theta L(z|e,\theta) f_\Theta(\theta) \cdot dz$$

Equation 4-88

Finally, the expected value of sample information is obtained:

$$EVSI(e) = E_Z[CVSI(z)] = \int_z \upsilon_{tz}(z) f_z(z|e) dz$$

Equation 4-89

$EVSI$ expresses the expected utility gained from performing the inspection e. This relationship can now be used to compare different inspection techniques. With increasing information quality of the inspection method, $EVSI$ asymptotically reaches $EVPI$.

As already stated above, the decision problems in optimal maintenance planning are represented by a decision tree. In application of the concept, several inspection decisions must be modeled at different points in time. Therefore, it has to be assumed that a failure event is a terminal event in the decision tree, Figure 4-68.

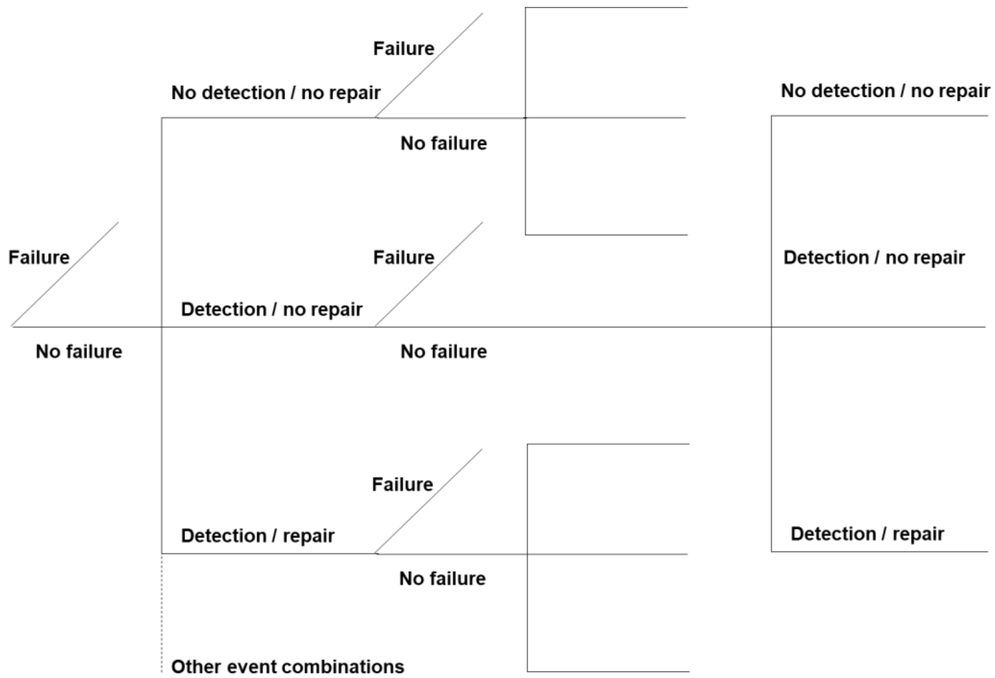


Figure 4-68: Generic decision tree in maintenance planning

Concerning the inspection actions, it must be determined:

- Where to inspect → location of inspection
- What to inspect → indicator of the system state
- How to inspect → what kind of inspection technique
- When to inspect → time of inspection

Also, the costs of an inspection strategy must be determined. Initially, the number of decision tree branches to consider must be evaluated:

$$n_b = n_a^{n_{Insp}} + \sum_{i=0}^{n_{Insp}} n_a^i$$

Equation 4-90

To reduce the considerable amount of probability evaluations two alternative simplification assumptions are possible.

1) A repaired element behaves like a new element
2) A repaired element behaves like an element which has no indication in inspection

Both simplifications assume statistical independence of the repaired element from the element before the repair action - Figure 4-69.

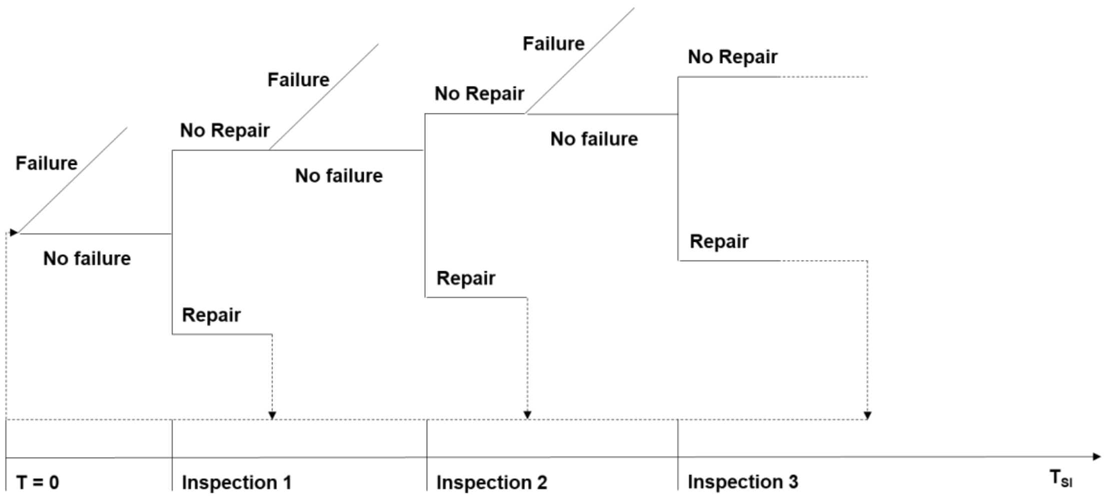


Figure 4-69: Simplification of the RBI decision tree for repaired elements

Problematic in this modelling aspect is that repairs are often tailor-made and not pre-defined. Thus, the time axis will be discretized in annual intervals. Consequently, the computation of the probability of occurrence of all branches in the decision tree is determined as follows:

$p_F(\underline{e}, d_d, T)$ … probability of failure in period T, given no repair in the period and dependent on the inspection parameters $\underline{e}$ as well as repair policy d_d

$\Delta p_F(\underline{e}, d_d, t_i)$ … annual probability of failure in year t_i given no repair and no failure before

$$\Delta p_F(\underline{e}, d_d, t_i) = \frac{p_F(\underline{e}, d_d, T_i) - p_F(\underline{e}, d_d, T_{i-1})}{\Delta t(1 - p_f(\underline{e}, d_d, T_{i-1}))}$$

Whereby:

- $p_I(\underline{e}, d_d, t)$ … probability of indication at time t given no repair before t → dependent on the inspection parameters $\underline{e}$ as well as repair policy d_d
- $p_R(\underline{e}, d_d, t)$ … probability of repair given no repair at all inspections before t → dependent on the inspection parameters $\underline{e}$ as well as repair policy d_d

Equation 4-91

Researchers use extensive round robin tests to evaluate the performance of inspection techniques. A measure to describe the inspection performance is the so-called probability of detection (POD). The amount of inspection performance models today is limited, because round robin tests for empirical models are expensive and empirical models for one application and one device cannot be transferred to other applications. Figure 4-70 describes the probability of detection of a specific inspection technique in dependence of the defect size qualitatively.

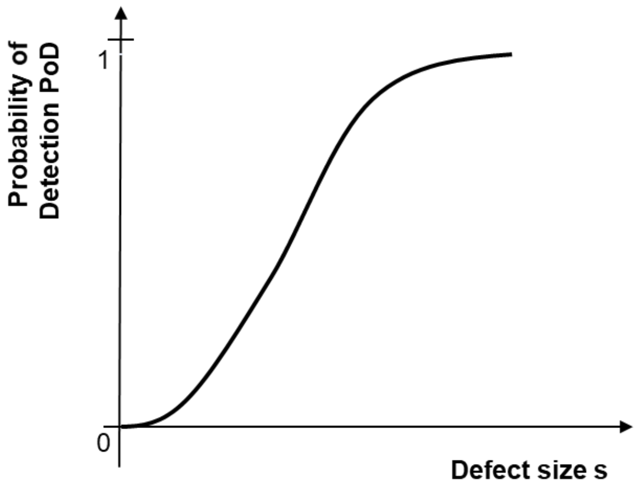


Figure 4-70: Probability of detection vs. defect size

The performance of a nondestructive inspection measurements is dependent on many parameters:

- Defect size
- Defect orientation
- Environmental condition
- Inspector performance
- Device
- Sensor
- Etc.

Mathematically the POD can be described as the mean rate of success when the specific inspection technique is performed and is exposed to various sources of uncertainties.

Basically, there are one and two-dimensional POD models.

An example for a two-dimensional POD-model is given in (Straub 2004):

$$POD(a,l) = \frac{\exp(\alpha_{2D} + \beta_{D,a} \ln(a) + \beta_{D,l} \ln(l))}{1 + \exp(\alpha_{2D} + \beta_{D,a} \ln(a) + \beta_{D,l} \ln(l)))}$$

Whereby:

- a … Crack depth
- l … Defect length
- α_{2D} … Parameter of the 2D-POD model
- $\beta_{D,a}$ … Parameter of the 2D-POD model

Equation 4-92

The counter event of flaw detection is the event of false indication. The probability of false indication (PFI) is defined as the probability of obtaining a defect indication where actually no defect is present. The probability of indication (POI) is represented by the merge of POD and PFI - Figure 4-71. The POI must be defined for a specific area.

$$POI(s) = PoD(s) + \big(1 - PoD(s)\big)PFI$$

Equation 4-93

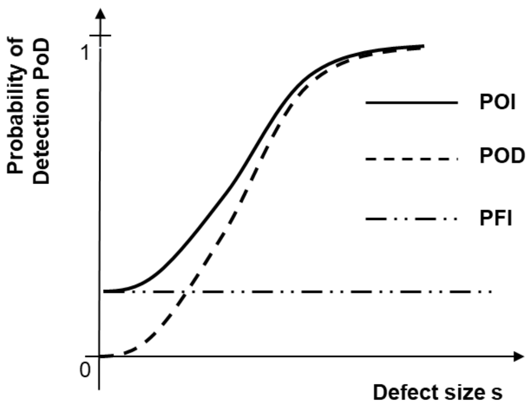


Figure 4-71: Probability of indication

The indication of an event is used to update the probability of failure after an inspection. Because the POD-function is a monotonically increasing function, the probability of detecting a crack smaller than or equal to s is $POD(s)$. $POD(s)$ becomes 1 for very large crack sizes.

The classic approach of the POD modelling has some short comings. The POD-function must be a distribution function, which is not always the case. Furthermore, it is difficult to integrate two-dimensional POD-functions. And lastly the classic models are not suitable for extension to the concept of POI, because the POI-function is not a distribution function. Straub (2004) developed a new formulation of the limit state function for inspection modelling.

For a given multidimensional crack size distribution $f_{\underline{S}}(\underline{s})$, the probability of indication is given as follows:

$$P(I) = \int_{\underline{s}} PoI(\underline{s}) f_{\underline{s}}(\underline{s}) \cdot \underline{s}$$

Equation 4-94

And it follows:

$$P(I) = \int_{\underline{s}} \left[\int_{0}^{PoI_{\underline{s}}} f_u(u) du \right] f_{\underline{s}}(\underline{s}) d\underline{s} = \int_{g_I \leq 0} f_u(u) f_{\underline{s}}(\underline{s}) du d\underline{s}$$

Equation 4-95

U is a uniformly random distributed variable with range from 0 to 1, where the limit state function is:

$$g_I = u - PoI(\underline{s})$$

Equation 4-96

Following:

$$g_I = z - \Phi^{-1}(PoI(\underline{s}))$$

Equation 4-97

For a crack size measurement it holds, whereby ε_m is defined as measurement error:

$$g_M = s - (s_m - \varepsilon_m)$$

Equation 4-98

Uncertainties inherited in the inspection performance models are:

- Variability due to scatter in the response signal (aleatory uncertainty)
- Statistical uncertainty due to limited set of trials in experimentally determined POD / PoI models (epistemic)
- Model uncertainty due to empirical nature of the parametric model (epistemic)

As described in chapter 4.6.3 the risk-based inspection optimization module in monitoring level 3 is mainly cost-driven. Therefore, the inspection cost need also to be modeled.

The inspection cost model integrates the following cost parameters:

- Expected costs of failure C_F
- Cost of inspection as a function of inspection technique e_t at time t
- Cost of repair C_R
- Interest rate r

The total expected costs during the service life period T_{SL} are computed as the sum of the expected failure costs, the expected inspection costs, and the expected repair costs:

$$E\left[C_T\left(\underline{e}, d_d, T_{SL}\right)\right] = E\left[C_F\left(\underline{e}, d_d, T_{SL}\right)\right] + E\left[C_I\left(\underline{e}, d_d, T_{SL}\right)\right] + E\left[C_R\left(\underline{e}, d_d, T_{SL}\right)\right]$$

Equation 4-99

The decision rule has a significant influence of the cost function. Some possible decision policies are summarized beneath, the decision policy needs to be defined as prerequisite:

- Repair all defects indicated at the inspection
- After indication perform a measurement and repair only cracks deeper than a_R
- Etc.

For the optimization procedure a maximum annual probability of failure is allowed Δp_F^{max}:

$$min_{e,d_d} E\left[C_T\left(\underline{e}, d_d, T_{SL}\right)\right] \; s.t. \Delta p_F\left(\underline{e}, d_d, t\right) \leq \Delta p_F^{max} \; t = 0, \dots T_{SL}$$

Equation 4-100

However, this optimization procedure inherits major restrictions:

- The minimum analysis period is one year
- The calculation of total service life is prohibitive

To level out the latter restriction, two simplification approaches are possible, the constant threshold approach and the equidistant inspection time approach (Faber et al. 2000).

Applying the constant threshold approach, the optimization parameter is the annual probability of failure ${\Delta p_F}^T$ and inspection is always performed in the year before ${\Delta p_F}^T$ is exceeded. It follows as new optimization problem:

$$min_{e,d_d, {\Delta p_F}^T} E\left[C_T\left(\underline{e}, {\Delta p_F}^T, d_d, T_{SL}\right)\right] \; s.t. {\Delta p_F}^T \leq \Delta p_F^{max}$$

Equation 4-101

Figure 4-72 shows a generic result of an optimized maintenance and inspection plan in the damage tolerant phase of a wind turbine supporting structure.

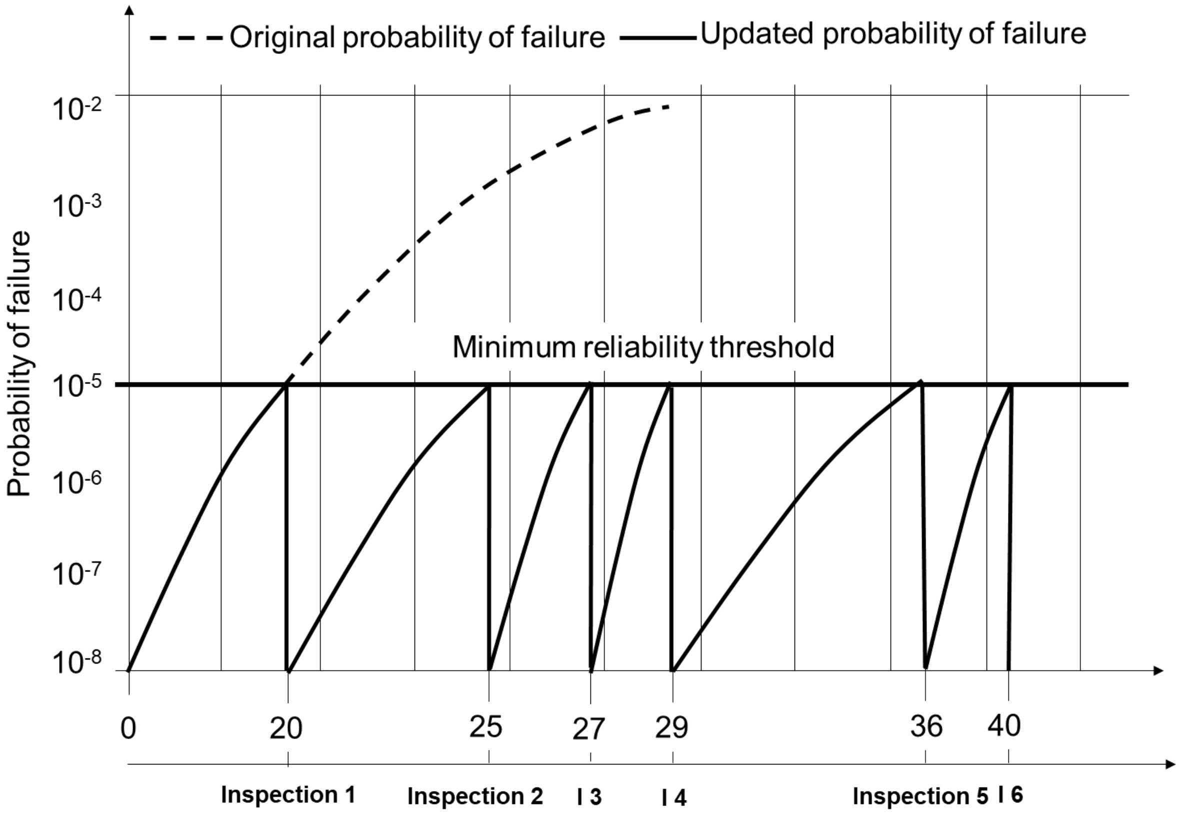


Figure 4-72: Generic inspection plan of wind turbine tower structure beyond fatigue design life

Finally, Figure 4-73 summarizes the subsequent steps and modules of the risk-based monitoring procedure proposed for monitoring level 3 and a probabilistic approach to operate and maintain wind turbine structures beyond their designed fatigue life.

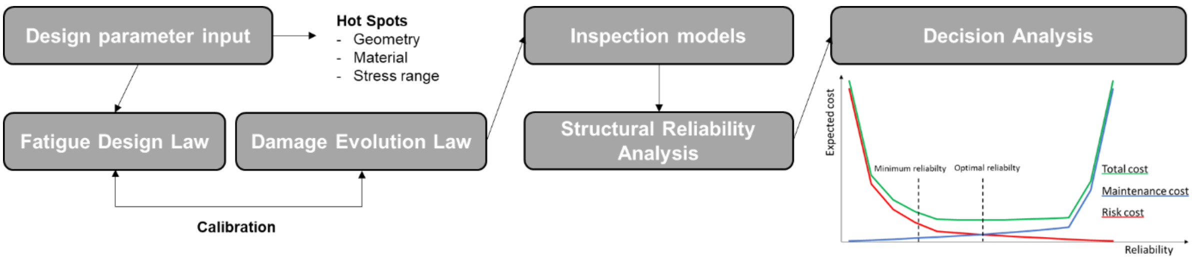


Figure 4-73: Overview of risk-based inspection approach for damage tolerant life of tower structures – adapted from (Straub 2004)

4.7 INTEGRATED ASSET MANAGEMENT DATABASE

To answer research question **RQ 9**, the following sections display the findings:

Which data management concept is most suitable for a wind turbine life cycle file?

There are numerous advantages in using Computerized Maintenance Management Systems (CMMS). However, it is of crucial importance to properly select, implement, and utilize CMMS. To date, no system has been implemented which pursues a completely holistic approach in all aspects of a CMMS solution. Database models of existing CMMS and RAMS/LCC systems are based on classic relational database architectures. A holistic data management is especially required in the wind energy and renewable energy industry.

Existing CMMS-solutions focus on explicit strength to analyze single components of a wind turbine system in a technological way. Superior data analytics focusing on chain of effects and tracking of root causes integrated throughout the whole plant life cycle do not exist so far. However, this would be a major step towards gaining a complete understanding to optimize asset maintenance management strategies and tactics.

4.7.1 PERFORMANCE OF SEMANTIC DATABASES AS ASSET MANAGEMENT TOOLS

The core focus of a holistic operational data base management system (ODBMS) for asset management purposes is the integration of information over the whole life cycle of assets and interdisciplinary cooperation and communication of data. Therefore, a horizontal (different life cycle phases, contractor, OEM, operator) as well as a vertical integration (actuator, sensor, control level management level) of its systems needs to be realized.

A modern ODBMS should be post-relational with no need for entity relationship models to be compatible with big data analytics, IoT-technology, and to run predictive analytics to its best performance. In an integrated asset management system, a main task is remote monitoring and diagnostics of many sub-systems and components. The process of gathering data relevant to the analysis tasks is most time consuming in many cases. Ontology-based data models are semantically rich conceptual domain models and can support service engineers in their data analysis tasks, because ontologies describe the domain of interest on a higher level of abstraction in a clear manner. In addition, ontologies have become a common and successful way of describing application domains in biology, medicine, and semantic web services (Kharlamov et al. 2014; Horrocks 2013; Poggi et al. 2008). There are several available formal languages in designing ontologies, e.g. the Web Ontology Language (OWL) is standardized by the World Wide Web Consortium (W3C). A mapping concept connects the relationship between the ontology and the scheme of the data, which by combining explicit and implicit information enhances the diagnostic performance of integrated asset management systems. Furthermore, it also enables the combination of static data and event streaming data, such as SCADA or sensor data for example. Compton describes best practices for semantic sensor network ontologies, integrating sensor data into a semantic asset management system (Compton et al. 2012; Brügge 2016).

Besides risk quantification and controlling, applying qualitative and quantitative methods and deploying obsolescence management, the ability to track the economical asset performance in such frameworks is essential, e.g. analyzing Life Cycle Costs (LCC) or the Total Cost of Ownership (TCO).

With reference to chapter 4.1 the role a semantic asset management system or database (ODBMS) plays in an integrated asset management systems is depicted in Figure 4-2.

The processes in operation and maintenance of wind turbine systems are skill and knowledge intensive. The required knowledge for holistic maintenance strategies must be managed and structured.

Semantic networks interconnect information. Due to the network structure, there are no limitations as is the case for common tree structures. The basic elements in semantic networks are Objects or individuals. Objects are assigned to Types. Objects and Types have characteristics and features. Features only related to Objects are so called Attributes. If characteristics interconnect Objects they are called Relations. The knowledge base in the semantic network emerges from these interconnecting relations. To model arbitrary circumstances, Attributes and Relations are to be defined accordingly. The gist of the Types and Objects concept is that every element occurs only once in the system – there is no redundancy. All relevant information is connected only once with the element – no dispersion of information. The basic ideas and name assignments go back to Ross Quillian (* 1931), which described the human representation of knowledge as semantic network (Minsky 2015).

The non-redundant elements can occur in different contexts via their interconnections in the semantic network. On principle the single elements are also separated from their designation in the system. Designations are inserted in the system via Attributes. Therefore, the multilingualism of a system can easily be implemented.

For structuring reasons, the Objects connected to a Type can be grouped under Sub-types. Every Attribute and every Relation is defined and connected to one Type. Through the interconnection of Types and Objects, the pre-defined characteristics are also valid for the single elements in the system.

A further basic concept in semantic networks is the concept of inheritance. Through inheritance, characteristics of Types are relayed to their Sub-types and Objects. Due to this, all relevant characteristics in the system are defined at the highest rank possible and are non-redundant.

4.7.2 INTEGRATED ASSET MANAGEMENT DATABASE – SYSTEM ARCHITECTURE

In 2015, a normative guideline for the design of an IAMS database for renewable energy plants was implemented in DIN SPEC 91303:2015-03. The guideline committee aimed at defining basic requirements for a so called Life Cycle File (LCF). Based on the basic set of requirements defined there, one can derive specific requirements for an ODBMS system for an integrated wind turbine asset management system.

The basic functions of an LCF are storage, administration, and management of all information incurring in the life cycle of a wind turbine. Thus, all incidents and the following actions during the operation phase of the turbine are managed.

First and foremost, an LCF must incorporate all necessary information for a safe and economic operation of a wind turbine system in chronological order and contain information on the entire life cycle of the turbine. Furthermore, it must provide information on property and responsibility in all aspects of asset management. Additionally, the judicative and normative background of wind turbines will need to be complied to (see chapter 2.4.2). At best, the file is edified during the planning phase of a wind turbine or at the beginning of the operational phase at the latest. Exceptions for already existing turbine systems are possible. An LCF must be applicable for different wind turbine systems and be flexible in terms of integrating an LCF file of a different subsystem from another wind turbine system. LCFs should not be deleted at the end of the turbine's service life. Performance intensive data analytics should not be conducted in an LCF, but in separate software modules, which are related to the LCF. Plant-based light statistic evaluations – histograms, etc. – should be possible. In addition to the already stated requirements, a digital life cycle file should represent an open application for every type of wind turbine. Furthermore, the information sets must be available over the whole life cycle of the wind turbine. If relevant, there must be an accurate balance between quick data access and archiving data. In addition, the digital architecture should consider scaling and expansion of the data structures as a key requirement. Data exchanges must be possible in a common format and data security at its best practice is to be applied, including allowing only authorized persons to access data. Optionally, there must be a possibility to reference specific plant data to external data pools for benchmarking purposes.

An LCF should be structured based on international guidelines for plant documentations systems, describing the relationship between information. A consistent plant documentation system will ease and structure the exchange of information of different players along the life cycle of a wind turbine system. The representing designation system for wind turbine systems which should be deployed is the so-called Reference Designation System for Power Plants (RDS-PP), which enables machine reading of component designations by using bar codes or RFID chips for example.

Figure 4-74 depicts the top-level life cycle file architecture.

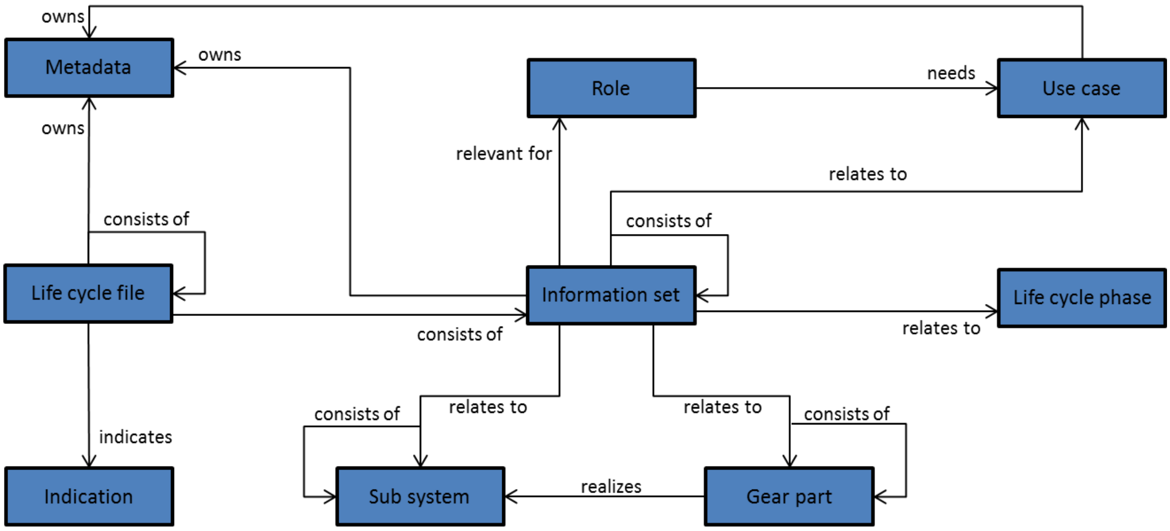


Figure 4-74: Top-level life cycle file architecture

The plant structure - Figure 4-75 - inherits a decisive role within the framework of a life cycle file, because it acts as a data backbone. All information sets refer to an element of the plant structure and carry a functional, product, and/or locational aspect. The plant structure is described by a system hierarchy based on the primary function of the sub system. The structural framework is independent of the product aspect. This meta data is especially important for designing, planning, monitoring, and analyzing maintenance processes.

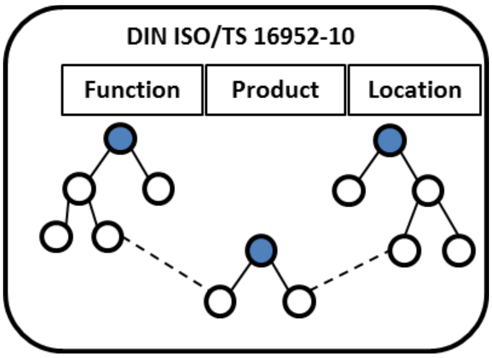


Figure 4-75: Plant structure data in LCFs

The documents are structured along their document classes. The basic hierarchy can be derived from main and sub classes along DIN EN 61355-1.

Operational data is integrated in the LCF by applying the information model of DIN EN 61400-25-x. The model is object-oriented and defines a specific hierarchy from a server over a logical device, a logical node to a data class with attributes. Attributes are to be defined concerning the operational task of the data channel. Specific data channel names are defined by DIN ISO/TS 16952-10 - Figure 4-76.

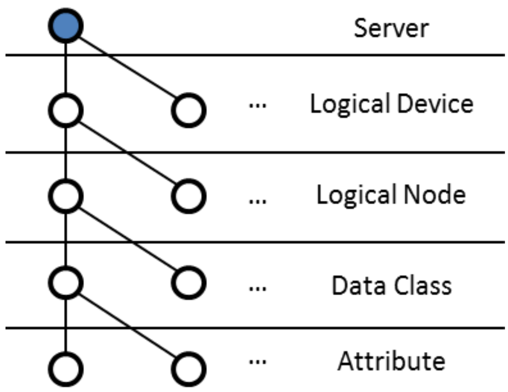


Figure 4-76: Operational data structure in LCFs

Every time step in the life cycle of the wind turbine is defined by a certain state or condition of the plant. Therefore, FGW developed the so-called ZEUS-key FGW TR7 D2. Basically, the ZEUS-key consists of two blocks of numerical code, whereby the first block code describes the overall condition of the plant and the second block code considers a component-based failure description and classification and defines a resulting or triggered maintenance task - Figure 4-77.

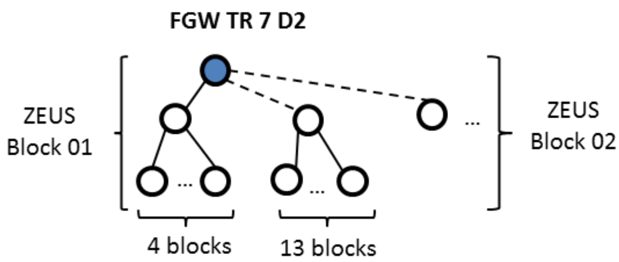


Figure 4-77: Incident data structure in LCFs

4.7.3 INTEGRATED ASSET MANAGEMENT DATABASE – IMPLEMENTATION

The information contained in the LCF must be consistent, up-to-date, complete, and reviewed and approved by the operator. It will need interfaces to the SCADA-system, the CMS-systems as well as to the SHM-system of the wind turbine. Every information set must relate to a plant sub system or an object within the systematic plant structure – realized within the RDS-PP structure.

Life cycle phases are defined for the wind turbine system as a whole. The different sub systems and components operate in their own defined product life cycle on the level of the smallest replaceable unit (SRU). Table 4-8 displays the defined life cycle phases within the service life of a plant. In operating life cycle files, it is important to transfer all relevant information into the next life cycle phase and to intercommunicate information between the different life cycle phases.

Table 4-8: Definition of life cycle phases of a renewable energy plant

No.	Life cycle phase (LCF)	Explanations
1	Planning	Technical analysis; economic analysis; market analysis; site analysis
2	Construction	Construction concept of plant; Construction concept of sub-components
3	Sourcing/Manufacturing	Provision of material and components
4	Erection	Erection of plant on selected site
5	Commissioning	Commissioning test of plant on site
6	Production	Power production phase; Operation phase of plant; Design life consumption
7	Maintenance	Servicing of plant and its components
8	Shut-down	Turbine out of operation
9	End-of-life planning	Analysis of end-of-life opportunities
10	Demolition	Deconstruction of wind-turbine
11	Rehabilitation / Recycling	Rehabilitation and another site; Recycling of plant components

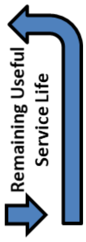


Table 4-9 displays the different roles and tasks within an integrated asset management system. The operator's main interest is an economic operation of the wind turbine or wind park, thus economic evaluations possibilities must be provided – e.g. life cycle costing analysis. Furthermore, information enabling the operator to conduct optimization of maintenance planning activities and the wind turbine's yield and availability data are of interest. The maintenance service provider – could but must not be a third party – requires information on the operating and wearing conditions of the wind turbine components. Furthermore, he needs deeper knowledge and historical data to conduct risk and criticality analysis in different levels and with different focus within the wind turbine system. Additionally, the system should provide him with possibilities to automate and control maintenance work flows for a higher level of transparency and efficiency conducting his performance. The infield service engineers might need PDA-support for performing their scheduled and unscheduled maintenance tasks, for documentation and communication within the IAMS framework.

Table 4-9: Roles and tasks in an integrated asset management system

Roles	Tasks	LCF
Operator	Legal responsibility for all aspects of the turbine	All phases
Plant manager	Taking care of the technical and economical operation management; site supervision	5 / 6 / 7 / 8
Assessor	Inspections of the plant and creation of technical surveys	1 / 4 / 5 / 6 / 7 / 8
Maintenance service provider	Planning maintenance tasks	7
Service engineer	Performing of maintenance tasks	7
Manufacturer	Planning and erection of the turbine	1 / 2 / 3 /4 / 5 /6
Regional authority	Supervision of the legal regulations	All phases

Considering a minimum data collection level to operate an ODBMS in a proper way, one can define the following minimum data collection requirements:

- Master data
  - Explicit plant identification
  - Designation of plant type
  - Date of commissioning
  - Beginning of data collection
  - Site location (longitude, latitude)
- Operational data
  - Wind speed (min, max, mean, std)
  - Wind direction (min, max, mean, std)
  - Plant power (min, max, mean, std)
- Incident data
  - Explicit and unique designation of event
  - Wind farm ID
  - Wind turbine ID
  - Time stamp of event
  - Time stamp of maintenance task conclusion
  - Functional state of wind turbine according to ZEUS block 01-02; at least to be categorized into “turbine not operational” or “turbine operational”
  - Type of event which caused the functional wind turbine state according to ZEUS block 01-04
- Component data per event
  - Explicit and unique designation of concerned component according to RDS-PP
  - Failure cause according to ZEUS block 02-05
  - Maintenance type according to ZEUS block 02-08
  - Maintenance measure according to ZEUS block 02-09
- Additional information (if available)
  - Functional state of element according to ZEUS block 02-01
  - Detection possibility according to ZEUS block 02-02

    - Detection symptoms according to ZEUS block 02-03
    - Failure mode according to ZEUS block 02-04
    - Failure consequences according to ZEUS block 02-06
    - Responsible person according to ZEUS block 02-10
    - Deviation of certified condition of wind turbine according to ZEUS-block 02-12
    - Replaced components and parts
    - Deployed materials
- Cost data
    - Overall maintenance cost per wind turbine and year
        - Fixed maintenance cost (service contracts)
        - Other fixed maintenance cost
        - Variable maintenance cost
        - Other cost
    - Economic maintenance performance data
        - Cost per event
            - Logistic cost
            - Spare part cost
            - Etc.

The ODBMS software developed in this thesis is based upon the open source and java-based frameworks STRUTS and SPRING. The goal of the open source project STRUTS in the Apache Software Foundation is to separate the model – in this case the semantic network – from the HTML-based views and the controller which passes information between the frontend and the model (The Apache Software Foundation 2018). SPRING is basically a java application framework used as inversion of control container (Pivotal Software 2018). The software package used for building the ontology and semantic network is supplied by k-infinity (i-views 2018). The ODBMS module which was developed in the framework of the thesis in collaboration with IABG mbH is named LIDOCWind – Lifetime Identity Documentation for Wind Turbines.

The programming environment of k-infinity is represented by the so-called Knowledge-Builder. The fundamental structure of the semantic network in LIDOCWind is modeled and managed here. Static data of the wind turbine – e.g. already existent RDS-PP objects – can be imported in various formats and linked to the semantic network. Relevant dynamic data – e.g. SCADA-data – can be connected to the semantic network via java-based interfaces. The graphical user interface (GUI) – called Front-End - is web-based. It can be accessed worldwide via web protocols from various end devices. The basic graphical design can be adjusted individually. More importantly, the views with which the users have to work can be adjusted in a user and/or task orientated manner. Field data from operation and maintenance activities – e.g. from service engineers doing their routine inspections – can be fed into the semantic network using the GUI. Serial developing of the semantic network in the Knowledge-Builder with operative Front-Ends is possible.

The basic structure of the k-infinity framework is displayed in Figure 4-78. The semantic network is stored in a semantic and object-orientated data base. A Mediator component provides and manages the semantic data base for developing activities. All other connected components access the data base via the Mediator component. Core objective of the Mediator is to ensure a consistent and persistent data storage for data actuality on all connected clients.

Application interfaces are provided by Bridge components. One part is the Java Application Programming Interface (API) others are http-based interfaces such as Representational State Transfer (REST) services to display the content of the semantic network over the HTTP-Protocol. Considering load distribution, it is possible to operate with several Bridges if necessary. Specific tasks – like the computation of the average share of maintenance cost per kWh – can be outsourced to Jobs which will be handled by the Job Processor components. The Admin-Tool deals with administrative tasks, for example data back-ups. Shell components enable importing and exporting data from the semantic network or integrating LIDOCWind into already existent operating procedures of the operation and maintenance activities. Imports are possible in tabular formats, databases with an Open Database Connectivity (ODBC) interface or vendor-specific databases like Oracle, MySQL, and PostgreSQL.

Single objects, parts of the network, or the entire semantic network can be exported – or imported - in the standard formats of the World Wide Web Consortium (W3C) RDFS (Resource Description Framework Schema) or OWL (Web Ontology Language). This functionality enables data exchange with other semantic network systems and tools.

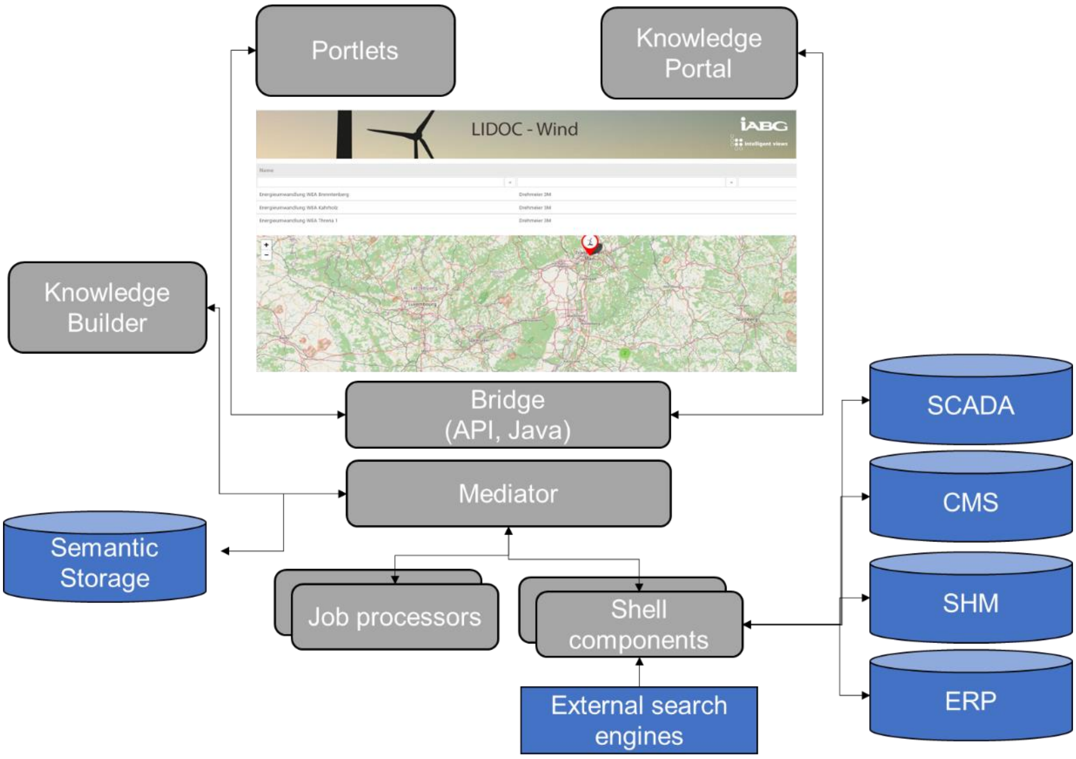


Figure 4-78: Basis software architecture of LIDOCWind in k-infinity

Figure 4-79 displays the implemented ODBMS software architecture within the LIDOCWind software solution.

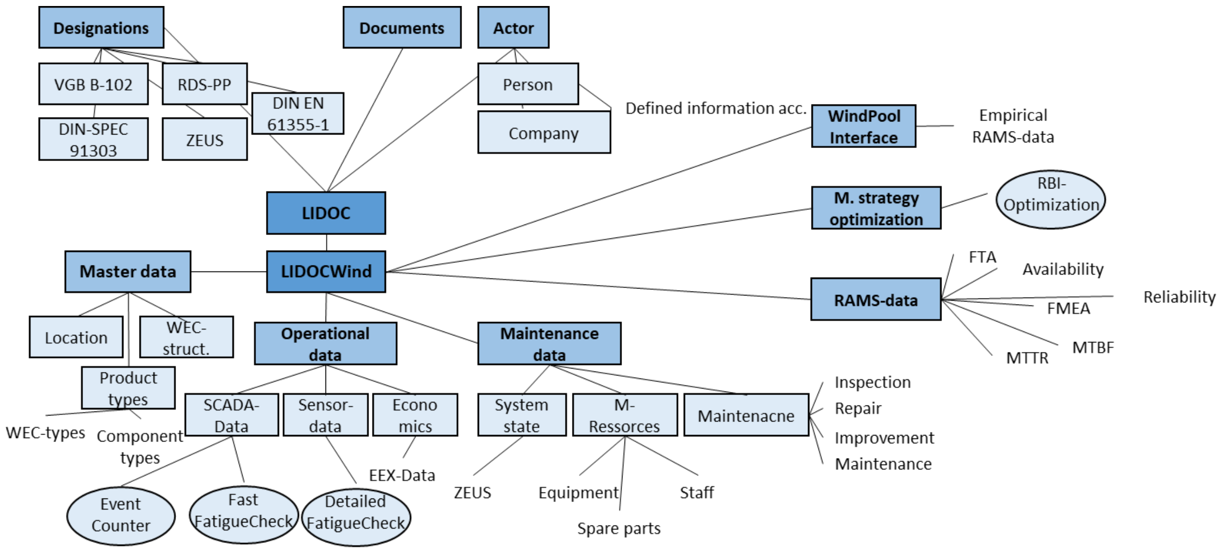


Figure 4-79: LIDOCWind structure

The next passages will state the fundamental rules which were used to structure the wind turbine system in LIDOCWind.

(1) Classification structure from "Big" to "Small"

The first designation rule deals with the inventory relationship in the wind turbine system. LIDOCWind classifies the components, from the overall wind turbine to the single fuse in the relevant sub systems. Every single object gets an independent classification code which is derived from the superordinate system.

(2) Objects have different aspects

Objects in the system can be seen from different angles. The main aspect of an object is always its functional aspect. In parallel, every functional aspect of an object is always connected with a product aspect and the accompanying product characteristics. Furthermore, all objects in the wind turbine system are complemented with the locational aspect. Every component – from the fuse to the wind turbine - has a well-defined installation location.

The functional aspect is marked with (=); the product aspect is marked with (-); the locational aspect is marked with (+) or (++) for the installation site of a wind turbine.

(3) The functional aspect can descend to the product aspect

Every basic function in the wind turbine system obtains one single flag. The next level then defines which product or product class is responsible for fulfilling the functional aspect. For example, the functional aspect hauling will be fulfilled by the product aspect pump.

(4) Objects with similar attributes are summarized in classes

The idea behind this rule is a progressing facilitation and clarity of the classification system. The fundamental rules are derived from the normative standard VGB B102 for power plants. For example, the class Storing bundles energy storages, material storages, or information storages of the system.

(5) Every system must guarantee autonomous functionality

This last rule helps define the system boundaries. All supporting functions of a system which are necessary to fulfill the basic function are integrated. Considering the generator system, the lubricant supply system must be part of the generator system.

Applying these rules in field for structuring real wind turbine systems needs a pragmatic attitude, considering the balance between integrity and practicability.

Master data in LIDOC

For precise recording of data in the wind turbine environment one needs a well-structured designation system which allows comparing data of any kind.

The master data architecture of LIDOCWind is therefore based on the Reference Designation System for Power Plants (RDS-PP) which is in worldwide application. The new guideline VGB-S-823-32-2014-03-EN-DE allows applying the designation system for wind turbines. The designation follows a functional order on component level and is vendor-independent. Therefore, the system enables independent and cross-national data comparability - Figure 4-80.

The concept of designation is based on the standard IEC 81346-2, which gives the fundamental rules for structuring principles and reference designation of industrial systems. The fact that RDS-PP is based on normative standards, promotes the acceptance in the industry. The system works object-orientated and takes functionality and workflow aspects into account.

RDS-PP allows the distinct designation of all relevant parts of a wind turbine. During the service lifetime of a component, different entities – such as strategy and design, engineering, construction, documentation, operation, maintenance, and recycling – must interact in the system. To enable clear processes and workflows – especially for operation and maintenance - it is necessary to implement a distinct designation of the wind turbine's components.

RDS-PP will become the worldwide industry standard for the basic designation of wind turbines. The rules which lead to the single designations of the components are clear-cut and their application is well described in the normative documents. To hinder hybrid designation systems in parallel to RDS-PP, a system must be structured completely along RDS-PP to claim the standard.

The first level of the master data structure is represented by **# Conjoint Designation**. The following data blocks define the longitudinal and latitudinal coordinates, country and region, and the project-specific wind turbine name (**WN** stands for Wind Onshore).

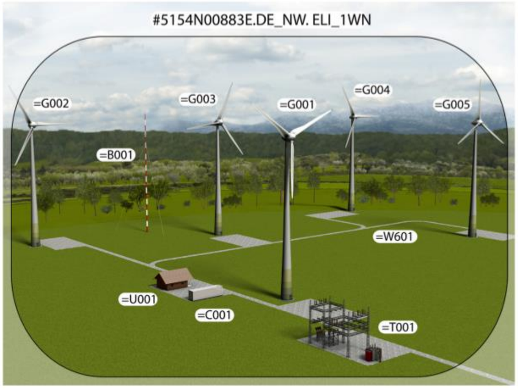


Figure 4-80: Basic RDS-PP structure (Königstein et al. 2007)

A master data RDS-PP code must be unique across the world. The internationally renowned coordinate system WGS84 is therefore applied in its decimal representations - Figure 4-81. Thus, RDS-PP can address any point of the world surface in a unique and simple way (the concept is already deployed by Googlemaps).

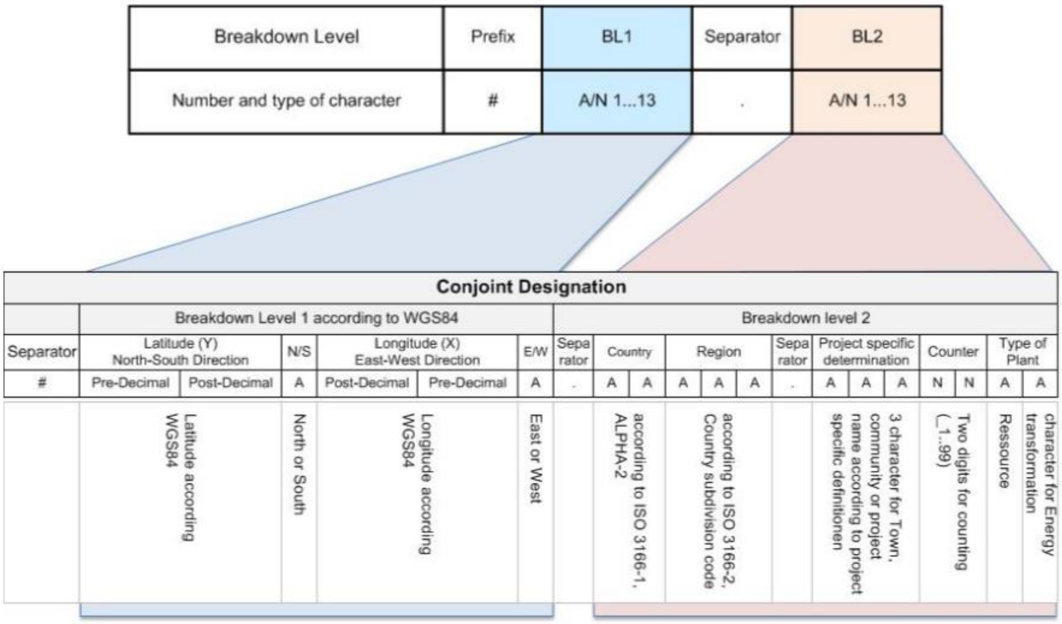


Figure 4-81: WSG84 geographical designation with RDS-PP (VGB-S-823-32-2014-03-EN-DE)

The next level of the RDS-PP designation system is represented by the functional classification levels of the wind turbine (indicated with the symbol (**=**)). The superior functional levels are represented by the **Main systems =G001** → G stands for wind turbines, the free digits are used for counting. After **Main systems**, the following level is **Systems =G001 MDL** which represents the Azimuth system. After that follows the level **Sub system =G001 MDL10** representing the Azimuth drive train. The last functional level is represented by **Basic function =G001 MDL10 MZ010** representing the Azimuth drive train 1. The next levels represent the product classification level and transition with the symbol (**–). =G001 MDL10 MZ010-MA001** represents the Azimuth motor 1. Normally, one product classification level is sufficient for wind turbine structures, which is represented by the level of **Assembly.** If necessary, the product classification can be extended to P2 -level, which is the level of **Components.**

The specific correlation to the installation location is not applied for the Type structure in the semantic network. Type classifications start at **Main Systems** level without numeration and end at classification level. Three underscores between the **Main system** and the **System** serve as placeholder guaranteeing uniform character lengths.

```
=G___MDA "Rotorsystem"
```

Installation sites and locations are implemented in the object structure. Hence, specific components of the wind turbine can be identified without knowing the relations in the network.

```
#5154N00883E.DE_NW.ELI_1WN "Wind Farm Elisenhof"
```

…

```
#5154N00883E.DE_NW.ELI_1WN=G001 UMD 29 "Turmsystem Turmfuß"
```

The network structure for types and objects in the master data area with RDS-PP designation is displayed in Figure 4-82. Types are categorized along the RDS-PP system, the structure emerges from defined relations between the types.

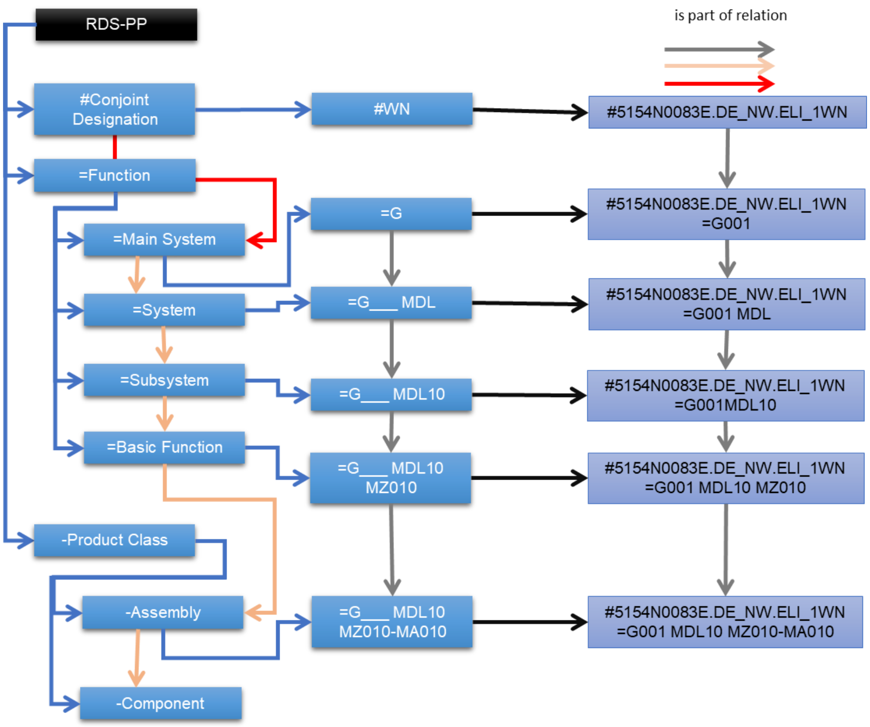


Figure 4-82: Master data type structure in LIDOCWind (Herrmann 2015)

In-service data in LIDOC

For a holistic monitoring and inspection strategy, it is crucial to develop an explicit classification of conditions, incidents, and causes in the wind turbine system. A new normative base of this idea is represented and implemented by the ZEUS-Code.

The ZEUS-code allows a distinct description of conditions which can be derived from the installed monitoring system (SCADA and/or CMS and/or SHM) and the data from on-site inspections. ZEUS stands as acronym for Zustands-Ereignis-Ursachen-Schlüssel. To build-up a pro-active asset and maintenance organization, the defined and accurate description of conditions, incidents and root causes is essential. The ZEUS-code describes current states, which can be derived from plant control and plant inspection. Whereby the description is carried out component-based and is linked with the RDS-PP designation system. Thus, it is possible to fully transparently manage asset life cycles of wind turbines with a worldwide unique designation system. ZEUS is sub-divided into two blocks with up to six sub-categories, Figure 4-83.

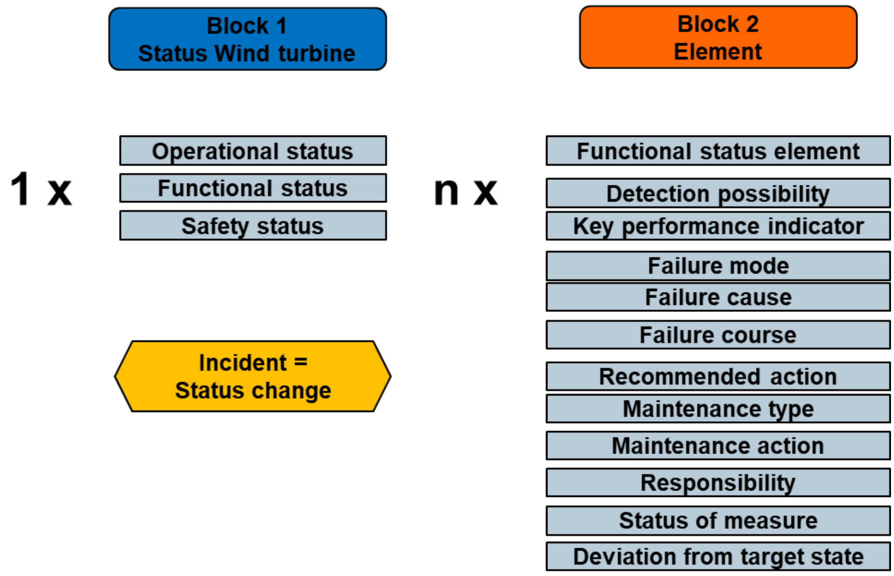


Figure 4-83: Elements of ZEUS status decription for in-field maintenance data

The defined conditions on component level are linked to the RDS-PP structured master data in LIDOCWind. Figure 4-84 describes graphically the Incident data structure in LIDOWind.

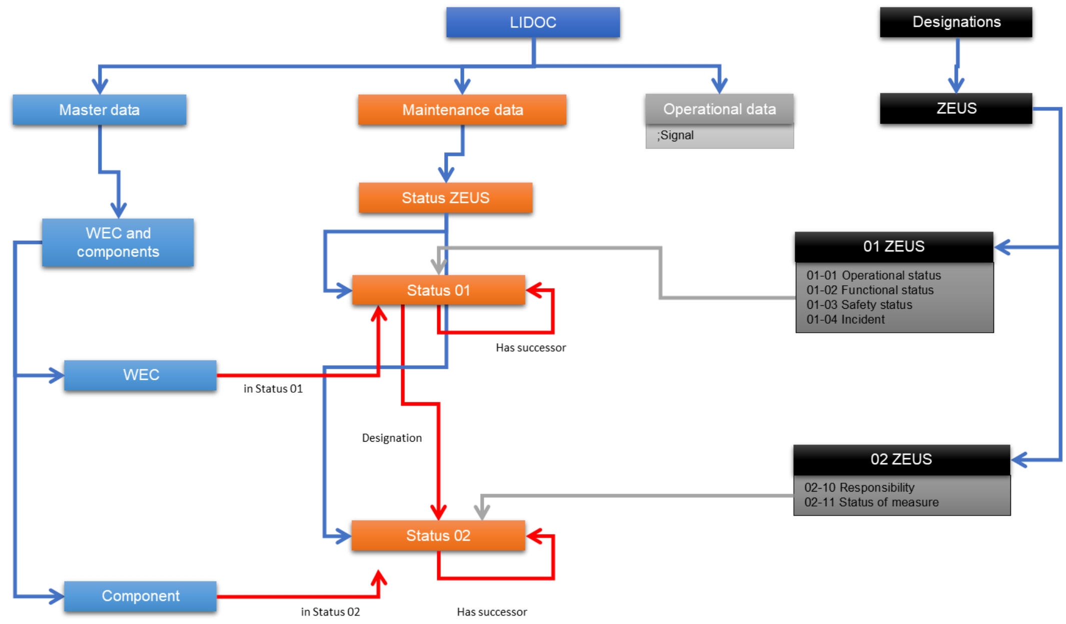


Figure 4-84: Incident data structure in LIDOCWind (Herrmann 2015)

The in-service data is transferred into the maintenance module, in which the actual life cycle file is building up. Figure 4-85 displays the maintenance module in LIDOCWind.

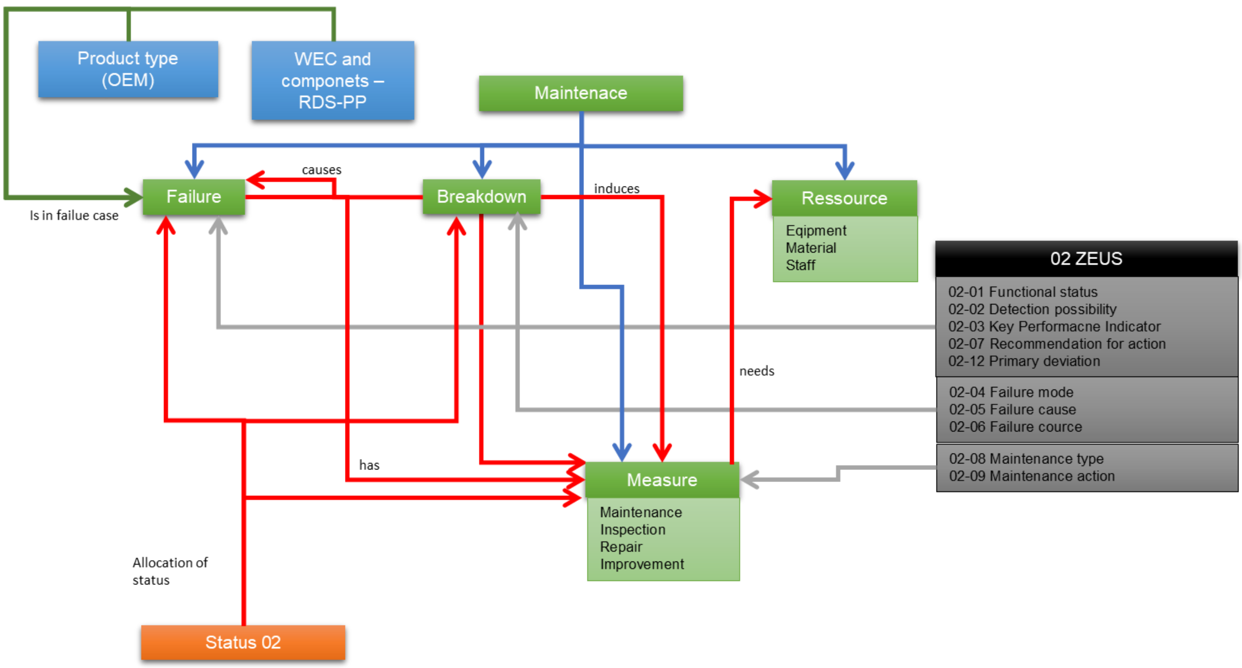


Figure 4-85: Maintenance module in LIDOCWind (Herrmann 2015)

The holistic Key Performance Indicator System for wind turbines (KPIS) which was developed in the framework of the dissertation is linked with LIDOCWind and the maintenance and inspection data base – chapter 4.5. The KPI definition logically is performed on a subsystem failure case level. The KPIs are grouped into four general families, fatigue assessment, structural integrity, operability and economics.

5 CASE STUDIES AND FURTHER ASPECTS OF IAMS APPLICATION

5.1 MACRO ECONOMICAL EVALUATIONS AND IMPACTS

To answer research question **RQ 1**, the following section displays the findings, whereas the research questions were partly answered in chapter 1.2, this section focusses on quantitative evaluations:

Which overall macro and micro economic role and importance can a holistic asset management concept for wind turbines have in the energy transition process?

Europe is currently in the energy transition process from conventional and fossil power technologies to renewable energy technologies. In the coming years more and more wind turbines will exceed their designed lifetime of 20 years. Predictions say that in the year 2020 we will have 8,200 turbines over 20 years in operation (Bange et al. 2017). Despite having less turbines installed, the offshore sector will play a key role in the upcoming future. The core problem faced by the offshore maintenance business is the high maintenance cost – 2 to 4 times higher than in the onshore sector (IRENA 2012). For more detailed analysis of the global and European wind energy market see (Geiss 2014).

Prior to analyzing economic aspects of asset management concepts in the wind industry, an understanding of the cost structure is necessary.

On the highest level, the cost structure can be subdivided into investment cost and operation cost. Furthermore, the investment costs are categorized in primary investment cost and secondary investment cost. Main cost drivers are the following subsystems: gear box, rotor blades, generator, and particularly the tower structure. The specific investment costs of wind turbines rise with increasing hub heights but decrease with increasing power of the turbine. This correlation is led by the high costs of the supporting structure of turbines. The specific tower costs rise with increasing turbine power. On average, the primary investment cost shares of the tower structure range from 24 % to 32 % for a wind turbine in the onshore market. In comparison, rotor blades on average range from 21 % to 24 % of primary investment, and the gearboxes cost from 10 % to 18 % of primary investment. These three subsystems represent the most important cost shares of the wind turbine and are of high importance from an asset management point of view. The secondary investment costs comprise the foundation of the wind turbine, the grid connection, as well as prior planning activities. The main cost share of on average 18 % is occupied by the foundation costs.

Figure 5-1 illustrates the investment cost structure of an exemplary 3 MW onshore wind turbine in Southern Germany.

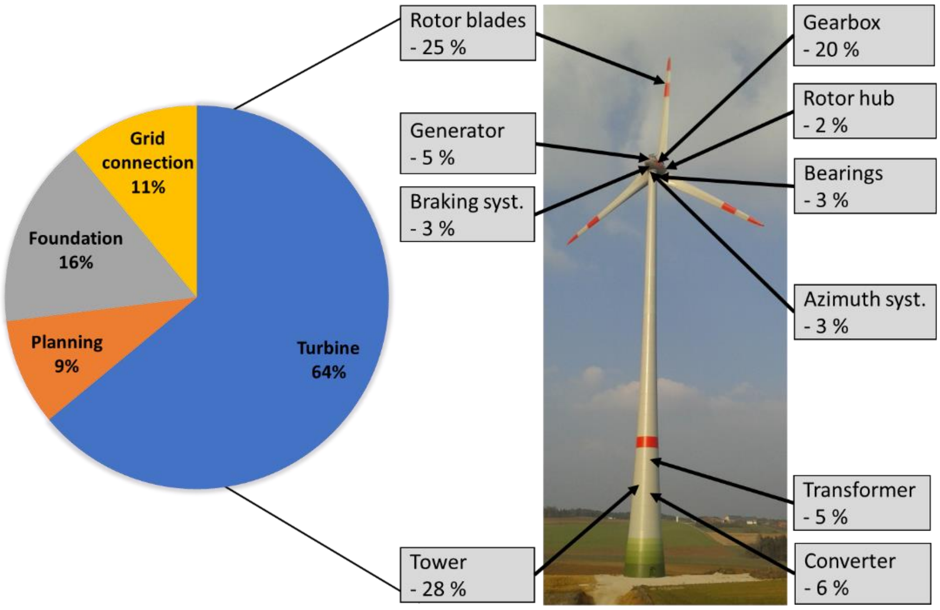


Figure 5-1: Cost structure of a 3 MW Wind Turbine System (Geiss 2014)

The second main cost category of wind turbines is the operating cost. The operating cost comprises all expenses necessary to ensure a safe and reliable operation of the turbine over the whole life span. Core expenses are maintenance and repair, leasing costs, commercial and technical operation management, insurance cost, and savings.

To proceed with the analysis of the distribution of operating costs it is appropriate to subdivide operating costs in first and second halves of the planned lifespan of a wind turbine project. Figure 5-2 shows the proportional distribution of operating expenses of an average onshore wind turbine project. Most importantly, the high amount of maintenance and repair as well as the increasing development in the second half of the life span is remarkable. In the second half of the lifetime, wind turbines cause 30 % to 43 % more O&M costs compared to the first half.

The renewable energy branch in Europe is currently under cost pressure in the energy transition process. On the route to a renewable energy system the challenge is to further reduce the energy production costs of the different technologies.

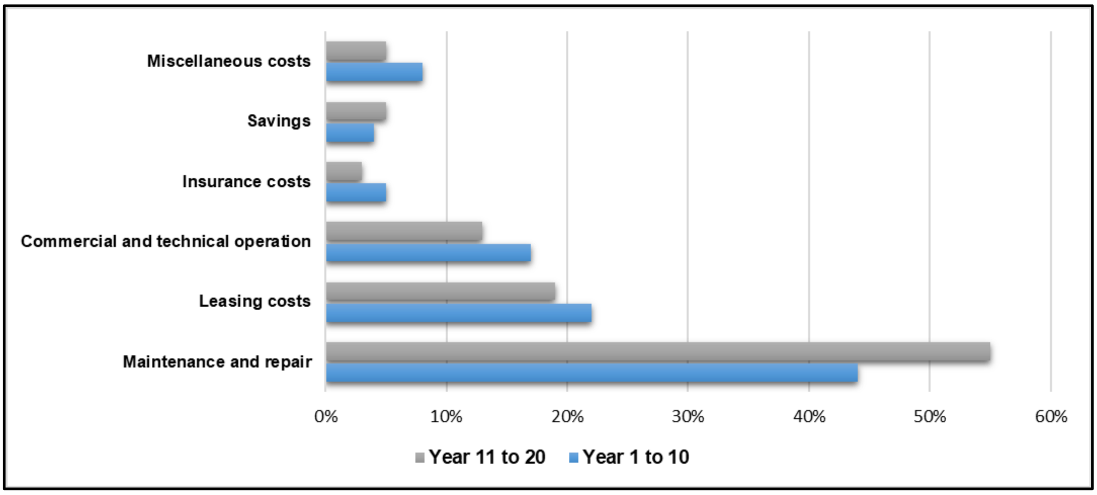


Figure 5-2: Proportional distribution of operating expenses (Geiss 2014)

First, the macro-economic potential of an integrated asset management system for wind turbines is object of investigation.

Germany spent approx. 30 bn. € in 2017 on feed-in tariffs and other subsidies for renewable energy sources (Bundesministerium für Wirtschaft und Energie 2017). However, wind energy already covers a major part of renewable capacities in the power system and represents a valuable development base. The key concept from a macro-economic standpoint should be to reduce the levelized cost of energy (LCOE) of wind energy. Applying the concept of LCOE, the streams of costs for wind energy are converted to a net present value using the time value of money. In general, the LCOE represent the price at which electricity must be generated from a specific source to break even over the lifetime of the project. All costs over the lifetime of a given project are summarized and included, discounted to the present time $t = t_0$ and levelized based on the annual energy production.

For wind turbines, the generated electricity represents future income and is discounted cash flow in the model. In C_t the annual overall costs are summarized. The parameter includes: General fixed and variable costs of the wind turbine project, all costs incurring from maintenance activities, insurance costs, as well as recycling costs of the wind turbine. For wind energy projects, there are no fuel costs to consider, which would normally represent an important parameter in economic evaluations of conventional power plants. The used discount rate for the study is exemplary derived from the theory of weighted average cost of capital (WACC). Under consideration of the current financial market, the WACC discount rate depends on the amount of equity capital in the project, the calculative return of equity capital, and the amount of bonded capital (Narbel et al. 2014).

One applicable formula to calculate the LCOE with this approach is the following:

$$LCOE_{Wind} = \frac{I_0 + \sum_{t=1}^{n} \frac{C_t}{(1+i)^t}}{\sum_{t=1}^{n} \frac{Y_{el}}{(1+i)^t}}$$

Equation 5-1

The goal of this approach is to enable the comparison of the energy production costs from different conventional and renewable sources from a macro-economic perspective. The method of levelized cost of energy is not suited to give evidence to the cost effectiveness of a certain wind turbine project. For such purposes, one needs a defined cash flow calculation over the lifetime of the project. Furthermore, the resulting prices of the LCOE approach cannot be compared to current energy prices in the energy stock market. The stock prices are dependent on weather and grid conditions and mainly influenced by the global market conditions in short term. These effects cannot be represented with LCOE prices.

Figure 5-3 compares the different main energy converting technologies which are currently available in the German energy system.

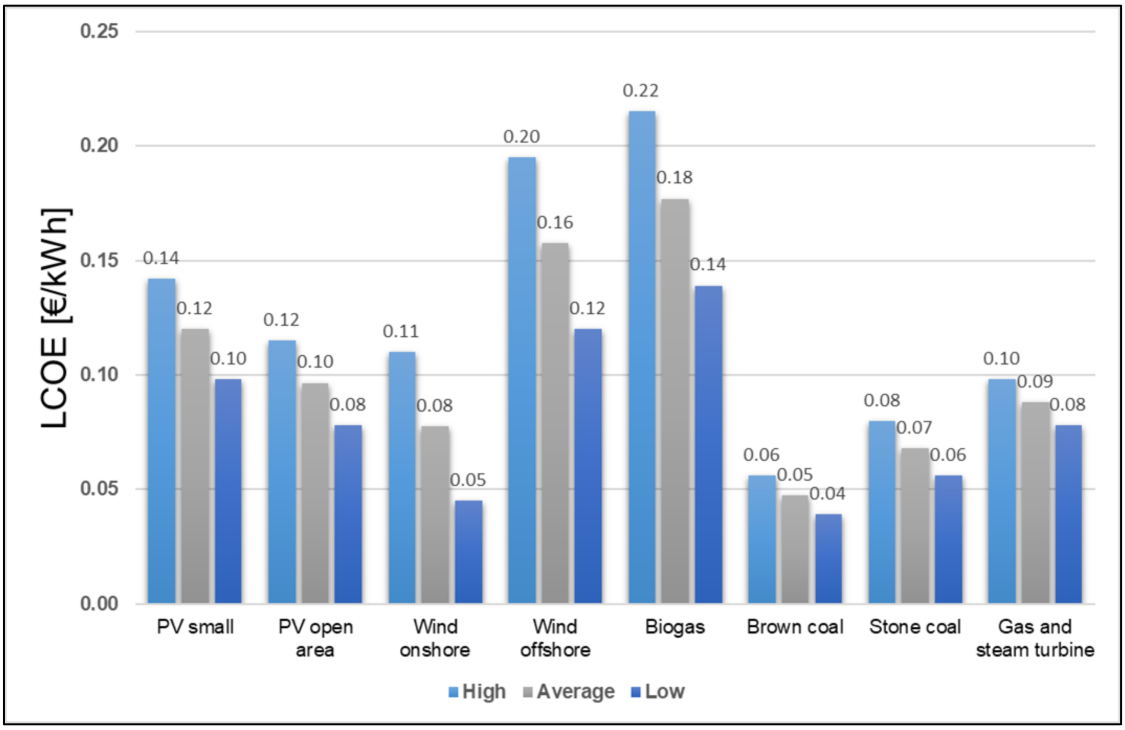


Figure 5-3: Comparison of LCOE of different energy conversion techniques (Geiss 2014)

Considering specific investment costs between 1,000 and 1,800 € / kW in the onshore area, the levelized cost of energy of onshore wind turbines ranges between 45 and 107 € / MWh. In good wind locations, onshore wind turbines are already able to produce power cheaper than conventional new coal and gas power plants. If this positive development continues, in future onshore wind turbines might be cheaper than average brown coal capacities in the energy system. Offshore wind turbine technology costs between 119 and 194 € / MWh providing specific investment costs ranging from 3,400 € / kW to 4,500 € / kW (Rohrig 2013).

LCOE of offshore technologies are approximately double the LCOE of onshore wind technologies. The expensive installation process and the high O&M costs contribute to this setting. But in general, the LCOE of renewable energy sources decrease in preparation of the future renewable energy system, while the LCOE of conventional power plants will continue to rise.

Figure 5-4 describes the LCOE of a wind turbine on an annual basis. The left side represents the cost side subdivided in the annual capital costs as well as the annual operation and maintenance costs. The right side represents the denominator side.

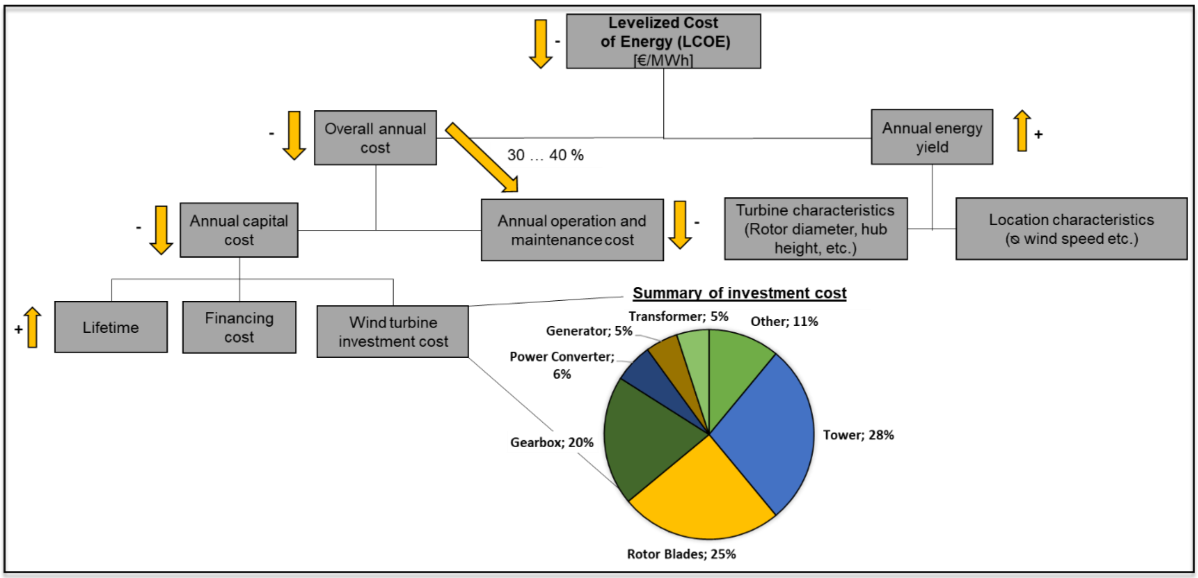


Figure 5-4: Constitution of levelized cost of energy for wind turbine systems (Geiss 2014)

The annual energy yield is dependent on the specific turbine characteristics as well as the location characteristics. Derived from technical and mathematical relationships to optimize and reduce the levelized cost of energy of wind turbine technologies, three main strategies connected with asset management systems for wind turbines can be clarified:

1) Lower O&M costs.

2) Increase power output.

3) Increase the lifetime of wind turbines.

To analyze the economic impact of integrated asset management systems in optimizing these three parameters, a generic sensitivity analysis was conducted.

Figure 5-5 describes the optimization domain for integrated asset management systems in wind turbine application from a macro-economic perspective.

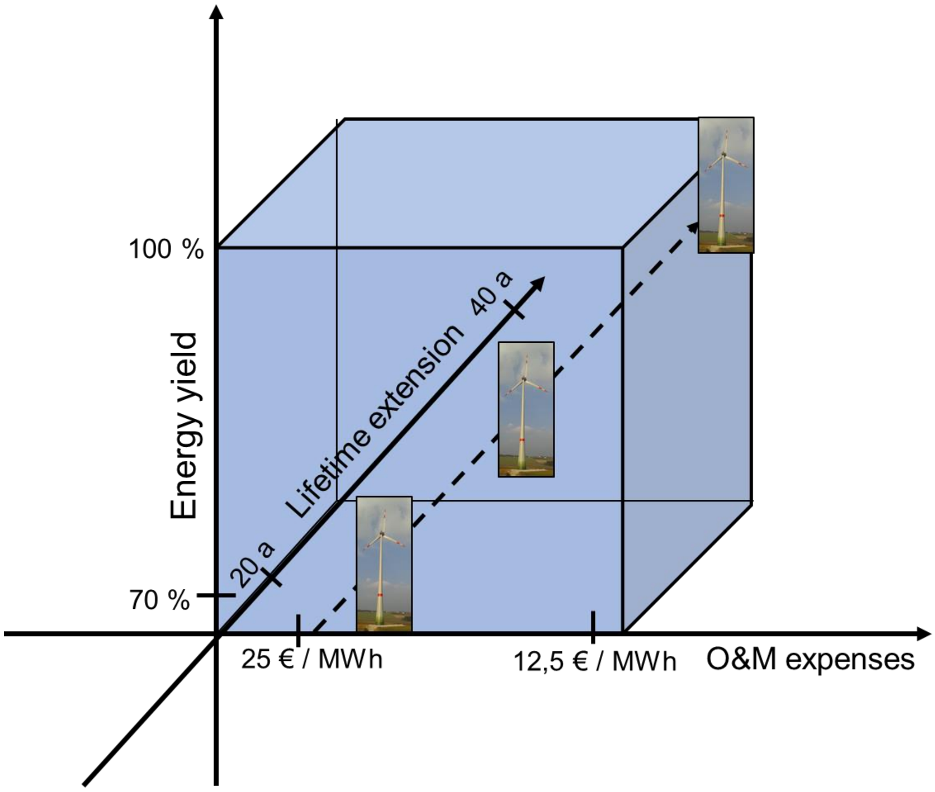


Figure 5-5: Optimization domain to lower LCOE of wind turbines

The sensitivity analysis focused on a typical onshore wind turbine class ranging from 2 to 3 MW. The overall operating costs in the years one to ten were fixed to 25.1 € / MWh on average. In the years eleven to twenty the operating costs were fixed to on average 26.3 € / MWh for the analyzing calculation conducted here. Furthermore, the discount rate was defined by 3.8 % according to the WACC-approach over the whole sensitivity analysis.

Firstly, the study modified the annual energy yield which corresponds to the IAMS function of helping increase the annual power output – e.g. through higher availability in the power grid. A typical value of 2,882 MWh/kW/a as 100 % reference value for the ideal onshore wind turbine was set - Y_{ref}.

As shown in Figure 5-6, the annual energy yield has a high impact on the LCOE. With every 10 % increase of annual energy yield the technology costs of onshore wind turbines fall by about 4.65 € / MWh on average.

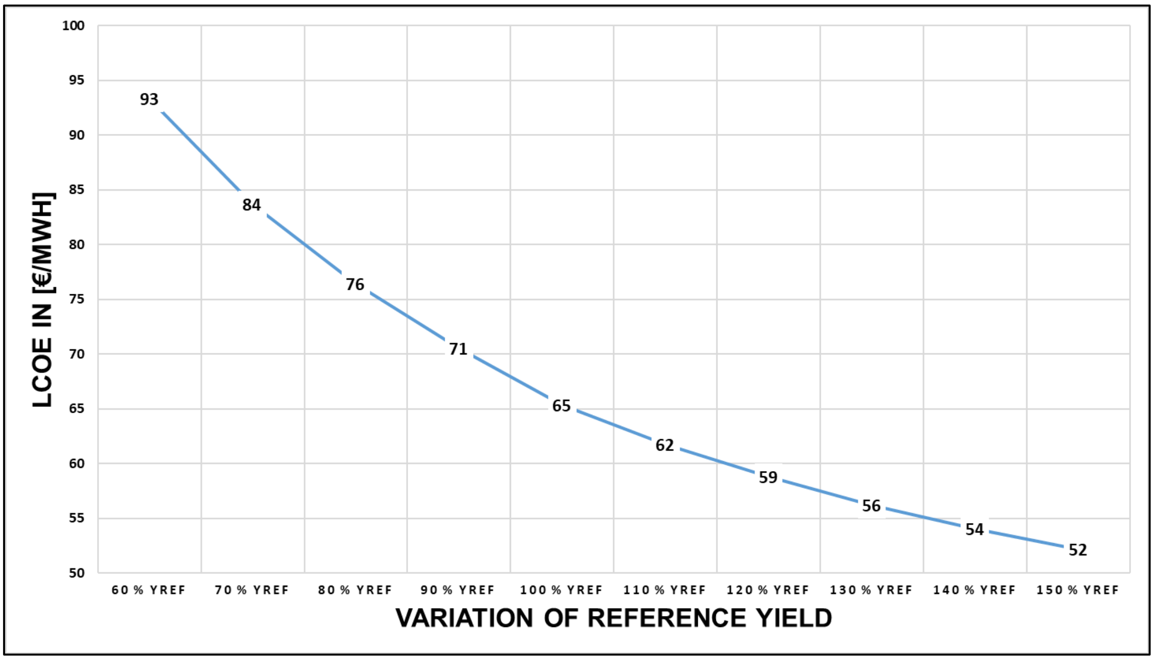


Figure 5-6: Effect of increased reference yield on LCOE through IAMS (Geiss 2014)

The next step was the variation of production costs, corresponding to the IAMS function of lowering the O&M expenses.

This step assumed a fixed typical onshore turbine characteristic set as object of investigation. With an 80% reference yield of 2,537 MWh/kW/a, the 2.45 MW onshore turbine with specific investment costs of 1.785 € / kW is typical for Southern German wind farm locations.

In ten steps the annual operation costs were decreased in steps of 5% relating to the initial configuration. Corresponding to the formula, every 5 % economization in the annual operating costs – mainly maintenance costs – reduces the technology costs by about 1.28 € / MWh. As shown in Figure 5-7, this variation has a linear decreasing effect on the LCOE. It must be said that an operating cost reduction of about 50 % might be difficult to reach with IAMS support, as the operating costs have fixed cost components which remain.

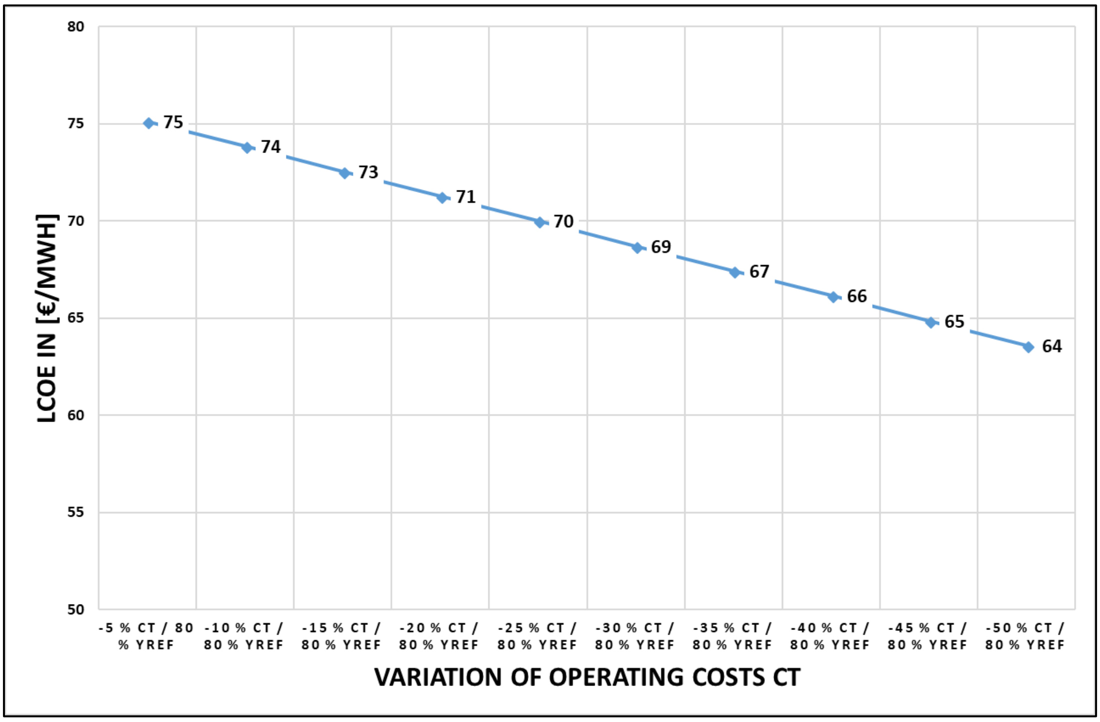


Figure 5-7: Effect of decreased O&M cost on LCOE through IAMS (Geiss 2014)

Finally, the lifetime of the wind turbine project was varied addressing the IAMS function of optimal lifetime management. The lifetime enhancement was modelled in ten steps increasing 5 years with every step - starting with the default lifetime of 20 years. Due to the fact that the operating costs of older wind plants will probably edge up, the calculation used a linear increase of operation costs of 1.2 € / MWh per decade extra lifetime (Bange et al. 2017).

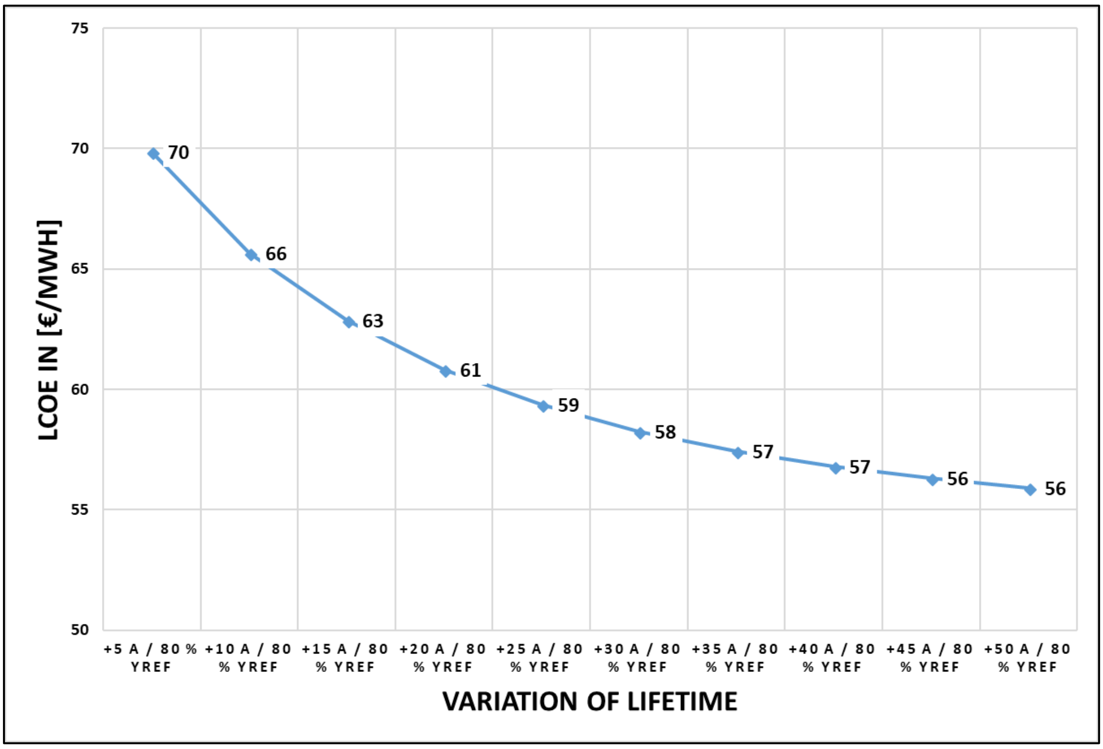


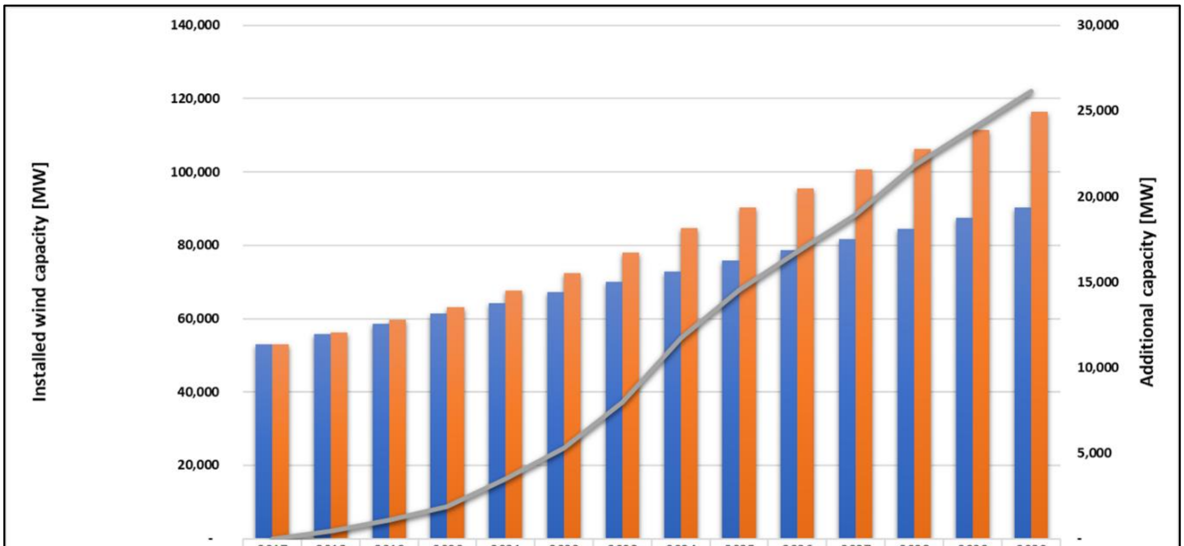
Figure 5-8: Effect of increased service life cost on LCOE through IAMS (Geiss 2014)

It is remarkable that in the first 20 years of additional system lifetime in the case study, every five years of additional service life led to a 5 % decrease in the LCOE of wind energy.

If wind turbines are not certified for an additional service life after the originally designed service life, operators need to shut down after 20 years, because their operating license lapses. Furthermore, it cannot be assumed that every wind turbine operator can ensure operation with a new wind turbine system at site and continue to feed-in clean energy.

For new wind turbine projects there is a complicated and currently rather inhibiting tendering process to install new wind turbines in Germany (Clearingstelle EEG / KWK 2016). Height restrictions and upcoming resistance and concerns of the local population additionally hinder the installation of new wind turbines. Thus, it is likely, that the overall energy system will lose wind capacity in the upcoming years, if there are no integrated concepts to prolong the service life of already existing wind turbines. As discussed above, it is predicted that in the year 2020 approximately 8,200 turbines will reach the end of their originally designed service life.

Further on, Germany will likely fail its climate saving goals for 2020 from the Paris Agreement (United Nations 2015). When it comes to emission reduction, the prolongation of existing wind turbine projects would contribute to additional reductions significantly (Deutscher Bundestag - Wissenschaftliche Dienste 2018). The new feed-in tariff law in Germany regulates an extension corridor for onshore wind turbines of 2,800 MW until 2020 and subsequently 2,900 MW per year (Clearingstelle EEG / KWK 2016). Figure 5-9 shows the presumed capacity development in two opposing scenarios, first if all wind turbines reaching their designed life of 20 years are shut down and second if all wind turbines older than 20 years are continued to operate in an IAMS concept, guaranteeing economic operation in a prolonged service life.

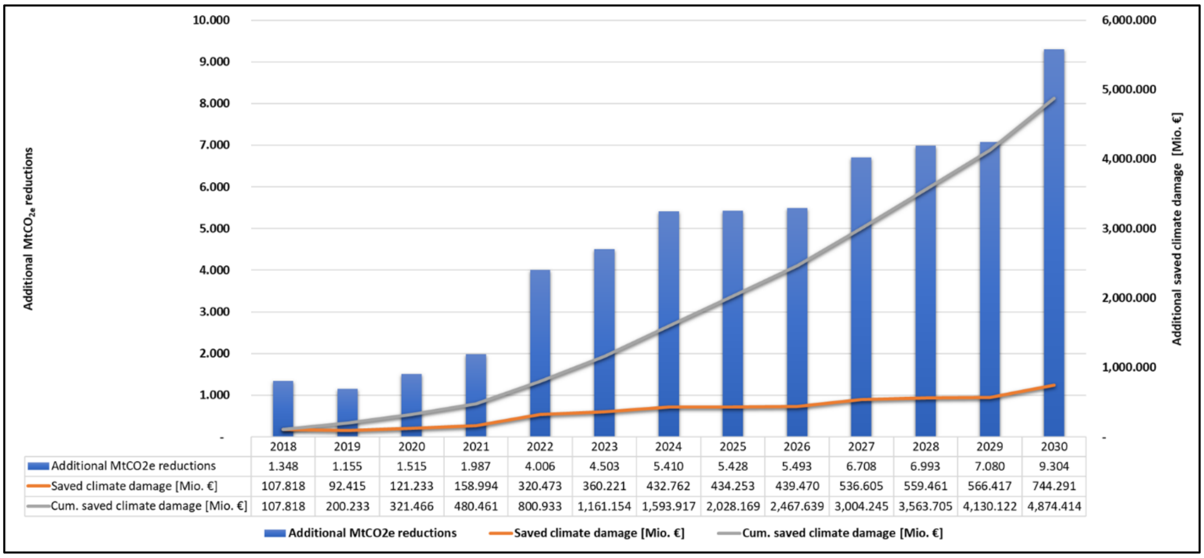


	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Shut down > 20 a	52,948	55,748	58,548	61,348	64,248	67,148	70,048	72,948	75,848	78,748	81,648	84,548	87,448	90,348
Continued operation > 20 a	52,948	56,213	59,623	63,223	67,736	72,448	78,048	84,693	90,408	95,519	100,604	106,354	111,432	116,479
Additional capacity	-	465	1,075	1,875	3,488	5,300	8,000	11,745	14,560	16,771	18,956	21,806	23,984	26,131

Figure 5-9: Wind onshore capacity scenario with and without remaining useful lifetime concepts

The additional possible wind capacity sums up to 26 GW in 2030. This shows how important an integrated asset management system and concepts to prolong the service life of already existing wind turbines are in a macro-economic climate saving perspective.

Figure 5-10 displays the prognostic macro-economic climate impact of IAMS concepts in Germany. The scenarios assume that all wind turbines – starting from 2018 – will not stop operating after 20 years but continue operating in the power grid.



	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Additional MtCO2e reductions	1.348	1.155	1.515	1.987	4.006	4.503	5.410	5.428	5.493	6.708	6.993	7.080	9.304
Saved climate damage [Mio. €]	107.818	92.415	121.233	158.994	320.473	360.221	432.762	434.253	439.470	536.605	559.461	566.417	744.291
Cum. saved climate damage [Mio. €]	107.818	200.233	321.466	480.461	800.933	1,161.154	1,593.917	2,028.169	2,467.639	3,004.245	3,563.705	4,130.122	4,874.414

Figure 5-10: Macroeconomic climate impact of IAMS concepts in Germany

This will lead to additional clean energy in the overall energy system and thus to additional reduction of GHG emissions. The additional reductions in GHG emissions are calculated using the life cycle emission level of coal-fired power plants as comparison. A coal-fired power plant emits 888 t of CO_{2e} compared to 26 t CO_{2e} for wind power plants (World Nuclear Association 2018). In that way, the German GHG emission reduction goal could profit from 9.304 Mt CO_{2e} additional emission reductions until 2030 and 1.515 Mt CO_{2e} until 2020. Industry associations predict a gap in emission reductions for the energy sector of 57 Mt CO_{2e} until 2020 in a worst case scenario (Förster et al. 2014). In sum, the overall cumulative saved climate damage can sum up to 4.874 Bn. € until 2030 in macroeconomic perspective for Germany.

5.2 MICRO ECONOMICAL APPLICATION CASE STUDIES

Concerning micro-economic effects of an integrated asset management concept for a specific wind turbine project, there are two approaches:

1) An investment costing approach – analyzing the rentability of a project by comparing negative and positive cost streams; elements which can be applied are the net present value (NPV), actuarial return, and the payback period
2) A life cycle costing (LCC) approach – only analyzing the cost site of a project or plant

In practice, the concept of total cost of ownership (TCO) is often used synonymous to a life cycle costing approach. However, TCO-concepts arose from an information technology basis and are rather not suited to evaluate industrial assets from a cost perspective (Gartner Inc. 2018). Firstly, micro-economic effects should be analyzed from an investment perspective.

Poor and unprofitable long-term investment decisions can influence a company's stability in the future and have retroactive effects on macro-economic scale. Thus, it is important to provide investment decision support. For practical micro-economic evaluations, three wind turbine projects were available for the scope of the thesis.

Table 5-1: Overview of micro-economic case study projects

	Wind turbine A	Wind turbine B	Wind turbine C
Turbine Model	Enercon E-101	Siemens SWT-3,0-113	Enercon E-40/6.44
Installed capacity	3 MW	3 MW	0.6 MW
Investment cost	5 500 000 €	6 000 000 €	500 000 €
Average annual yield	7 250 MWh average	9 116 MWh average	1100 MWh average
Hub height	135 m	143 m	65 m
Rotor diameter	101 m	113 m	43.7 m
Commissioning year	2013 / October	2015 / November	2000 / December

All analyzed wind turbines are built onshore, whereas wind turbine A and wind turbine B are in South Germany in a rather hilly terrain and wind turbine C in Middle Germany in a rather flat terrain. The respective micro-economic data was gathered directly from the operators and validated with a cost benchmark for German onshore wind turbines, published in Rehfeldt et al. (2013). To avoid overestimation due to beneficial policy effects from feed-in tariff regulations and to ensure general validity of the results, the micro-economic analysis used a moderate average scenario for positive cost streams. For both the annual yield of the wind turbine at site and the power renumeration. the arithmetic average value was used to simulate the rentability of the project over its presumed service life. The average annual yield assumption was retrieved from the respective location assessments of the wind turbine projects. The average power renumeration was calculated taking into account the preliminary feed-in tariff renumeration of the respective site and the presumed future energy price at the European stock market in a free and competitive power market in future (Bundesministerium für Wirtschaft und Energie 2017; European Energy Exchange AG 2018). Furthermore, all projects were calculated with a share of 25 % equity capital and a borrowing rate of 4.5 %. All case studies assumed a target payback period of ten years and target rentability of 8 % respectively.

Figure 5-11 displays the results of a 20-year basic scenario of wind turbine A. The average power renumeration was set at 71 € / MWh. The wind turbine is operated in a so-called full-service contract, in which a fixed annual maintenance cost payment is due for the service provider and variable maintenance costs are aligned along the variable power output of the turbine. From an operator perspective, such a constellation provides high investment security. However, various optimization aspects concerning maintenance and inspection and their effect on micro-economic investment rentability remain untouched or are only relevant for the service provider.

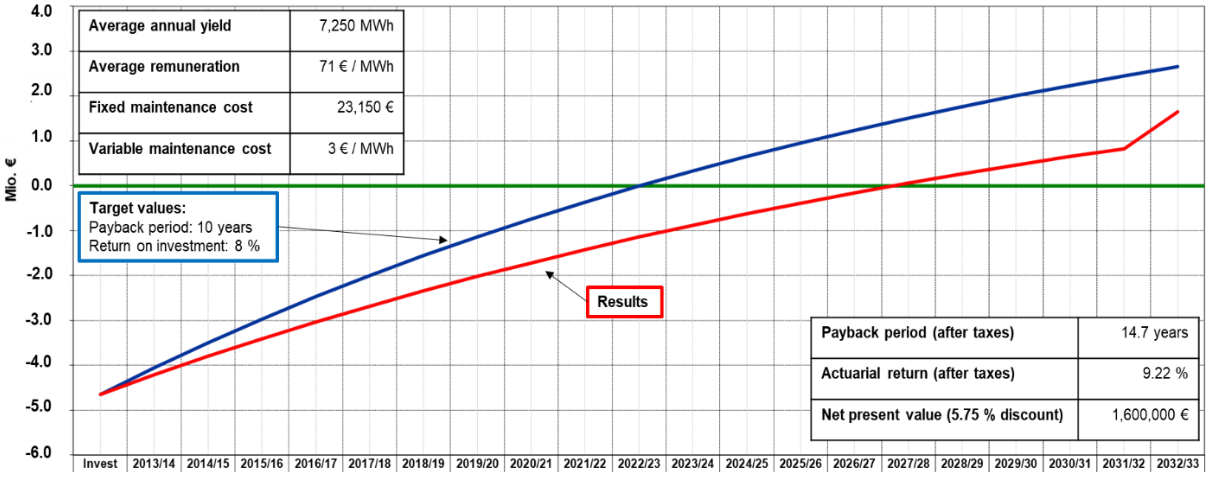


Figure 5-11: Enercon E-101 – Micro-economic rentability in a 20-year basic scenario

The payback period in the basic scenarios was 14.7 years and the net present value of the wind turbine investment after 20 years summed up to 1,600,000 €. Figure 5-12 displays the simulation of a prolonged service life of wind turbine A of about ten additional operational years. Further on, the simulation considered an increase in variable maintenance cost from 3 € up to 8 € / MWh (Rehfeldt et al. 2013). Compared to the basic scenario in Figure 5-12, the net present value of the project increased by about 31,25 % to 2,100,00 € after 30 years. The actuarial return remained at the same level. However, due to the increased maintenance cost, the payback period was prolonged to 17 years.

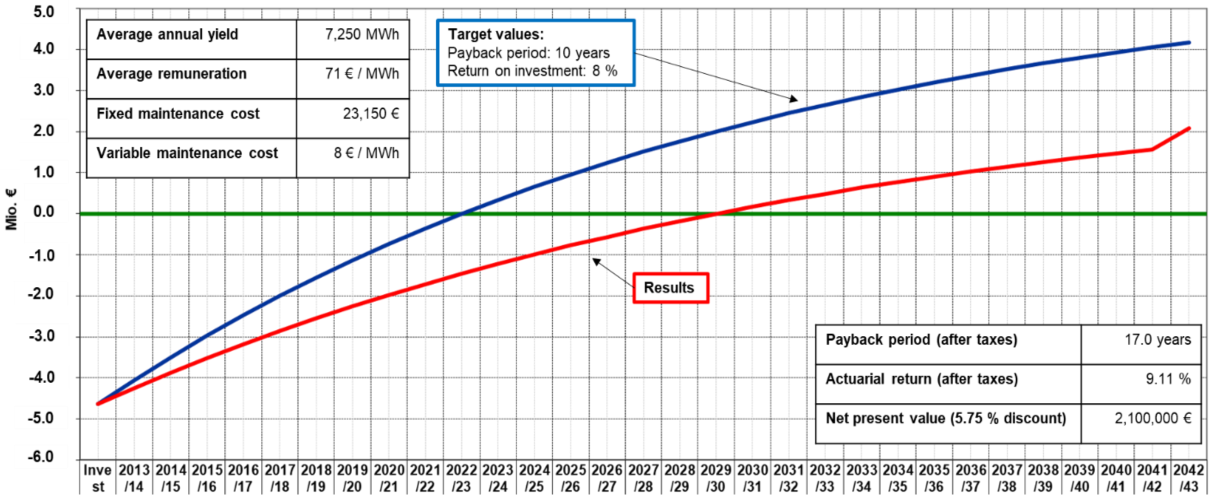


Figure 5-12: Enercon E-101 – Micro-economic rentability in a 30-year basic scenario

Figure 5-13 displays a 30-year advanced service live prolongation scenario in which the operator tries to avoid and prevent higher maintenance cost while investing in integrated asset management systems, which additionally results in higher availability of the wind turbine and consequently in a maximized annual power output. The cost of the provided asset monitoring and optimization services were assumed to be 5 € / MWh power output. On a micro-economic scale, this combination led to the most beneficial results for wind turbine A, with an NPV of 2,700,00 €, a payback period of 14,9 years, and an actuarial return of 10 %.

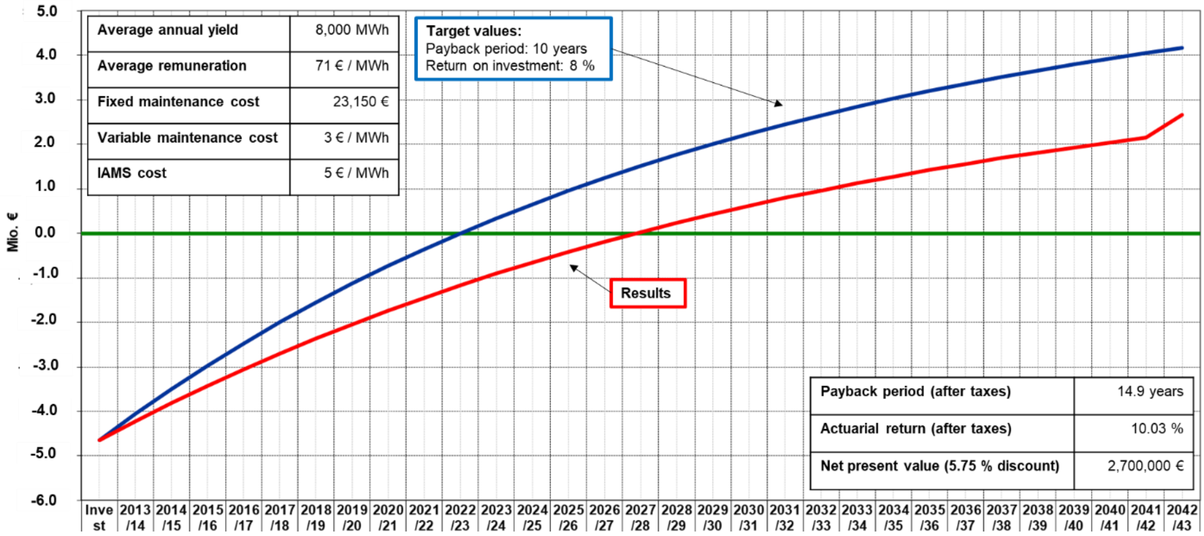


Figure 5-13: Enercon E-101 – Micro-economic rentability in a 30-year advanced scenario

The second case study dealt with wind turbine B which is an onshore wind turbine model of the newest generation, with an outstanding annual average yield situation of 9,116 MWh and a diminished average power renumeration of 68 € / MWh wind energy. Figure 5-14 displays the basic 20-year operation scenario: Payback period was projected with 13.2 years, actuarial return of about 10.13 %, and the net present value of 2,300,000 €.

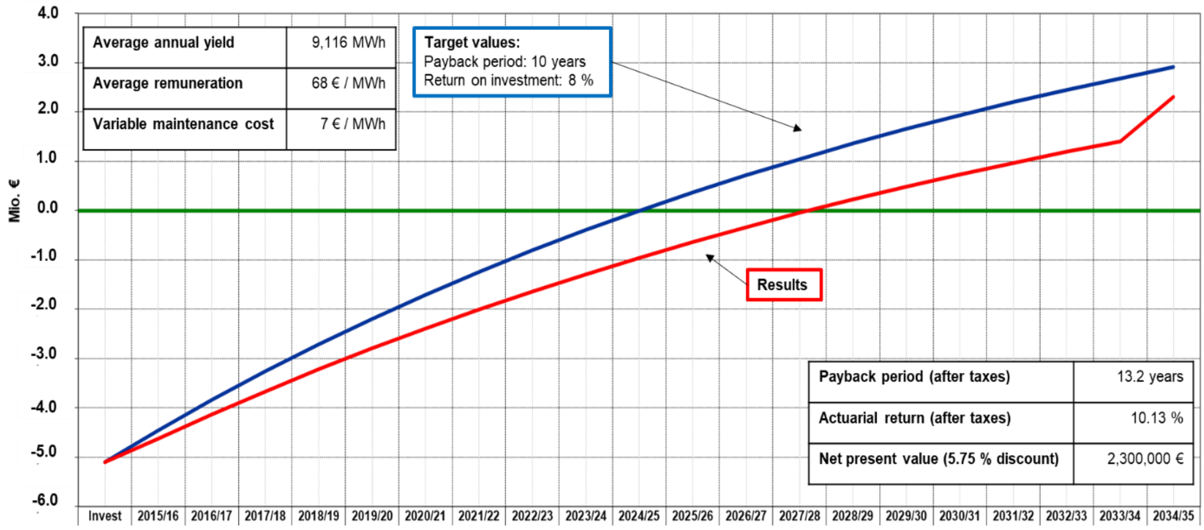


Figure 5-14: Siemens SWT-3,0-113 – Micro-economic rentability in a 20-year basic scenario

In analogy to wind turbine A, Figure 5-15 displays the projection of a prolonged overall service life of 30 years of wind turbine B. As assumed before, the variable maintenance cost were assumed to rise to 12 € / MWh in a conservative approach (Rehfeldt et al. 2013). 10 years additional operation increased the net present value of wind turbine B by about 26 %, compared to the 20-year basic scenario. Whereas the payback period was prolonged to 15.1 years, compared to 13.2 years in the basic 20-year scenario. Like the projection of wind turbine A, the actuarial return of wind turbine B remained unaltered in both basic scenarios.

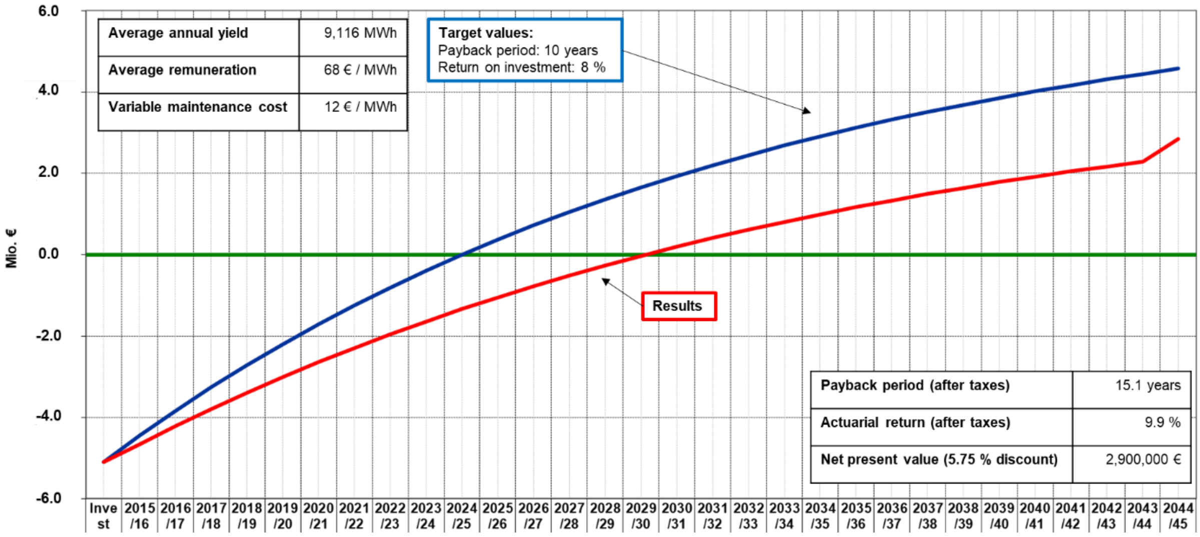


Figure 5-15: Siemens SWT-3,0-113 – Micro-economic rentability in a 30-year basic scenario

Figure 5-16 shows the advanced 30-year operational scenario in which the operator actively focused on avoiding additional maintenance cost and aimed on optimizing the availability of the wind turbine with optimal deployment of monitoring and inspection techniques. As in the preliminary scenario, the IAMS costs were assumed variable and considered with 5 € / MWh wind power output. It was conservatively assumed that the deployment of additional monitoring and inspections systems result in 180 additional hours in full load, which summed up to 9,800 MWh annual power yield. Thus, the operational optimizations led to maximized micro-economic results, with a payback period of 13.8 years and a net present value of 3,400,00 €, which is 17 % above the basic 30-year service life scenario and 48 % above the current 20-year service life basic scenario.

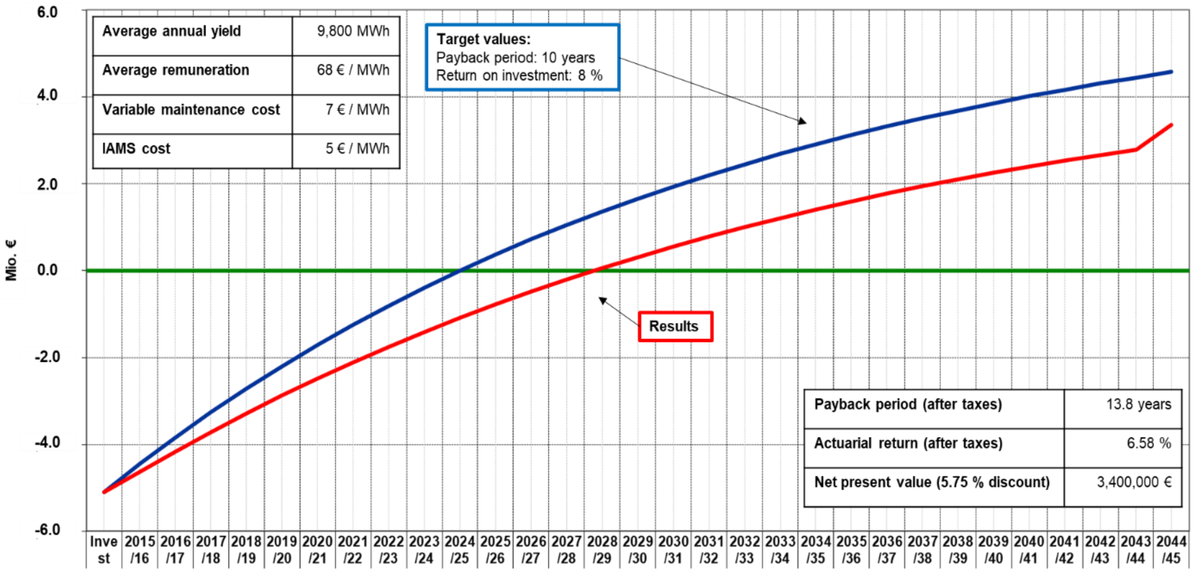


Figure 5-16: Siemens SWT-3,0-113 – Micro-economic rentability in a 30-year advanced scenario

Lastly, it was worthwhile to analyze an older wind turbine system with significantly lower annual yield parameters and lower investment and maintenance costs. Wind turbine C, the Enercon E-40, is a classic wind turbine system in the capacity class below 1 MW and is one of the most common wind turbines in the overall wind turbine population in Germany and Europe. Most of the systems were installed in the late 1990s and are therefore on the verge of the decision to choose a certified prolonged service life scenario. Figure 5-17 displays the basic 20-year service scenario for wind turbine C. The average annual yield fixed with 950 MWh, power renumeration was comparatively high with 71 € / MWh. The maintenance costs aligned along a service provider contract as in the case study of wind turbine A with 5,000 € fixed annual maintenance costs and a variable rate of 3 € / MWh. Running the simulation, the wind turbine was projected to realize a payback period of 12.3 years, an actuarial return of 10.66 %, and a net present value of 300,000 € after the designed 20-year service life period.

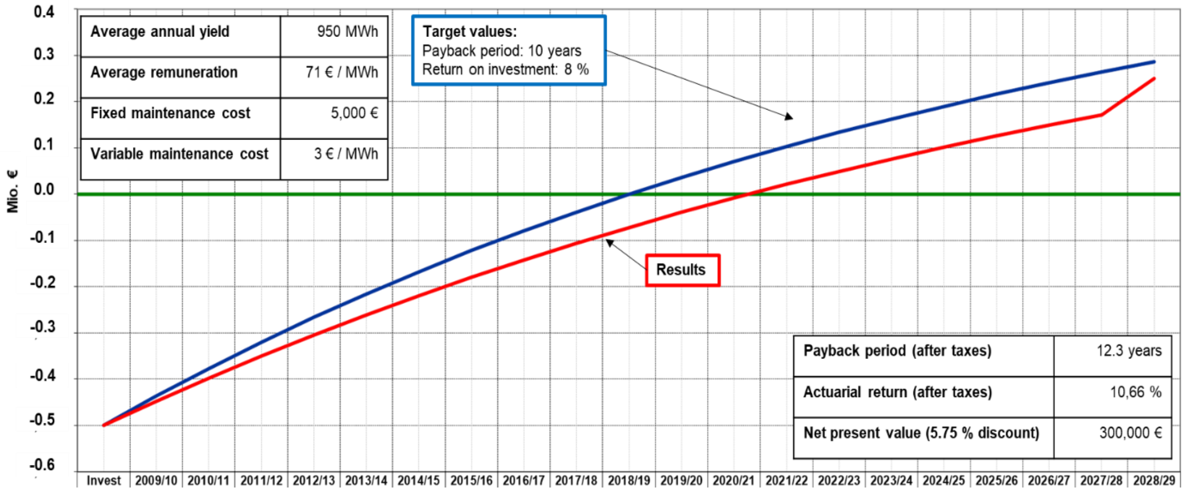


Figure 5-17: Enercon E-40/6.44 – Micro-economic rentability in a 20-year basic scenario

Simulating a prolonged service life of ten additional years and assuming increased maintenance costs did not result in positive micro-economic effects, as displayed in Figure 5-18.

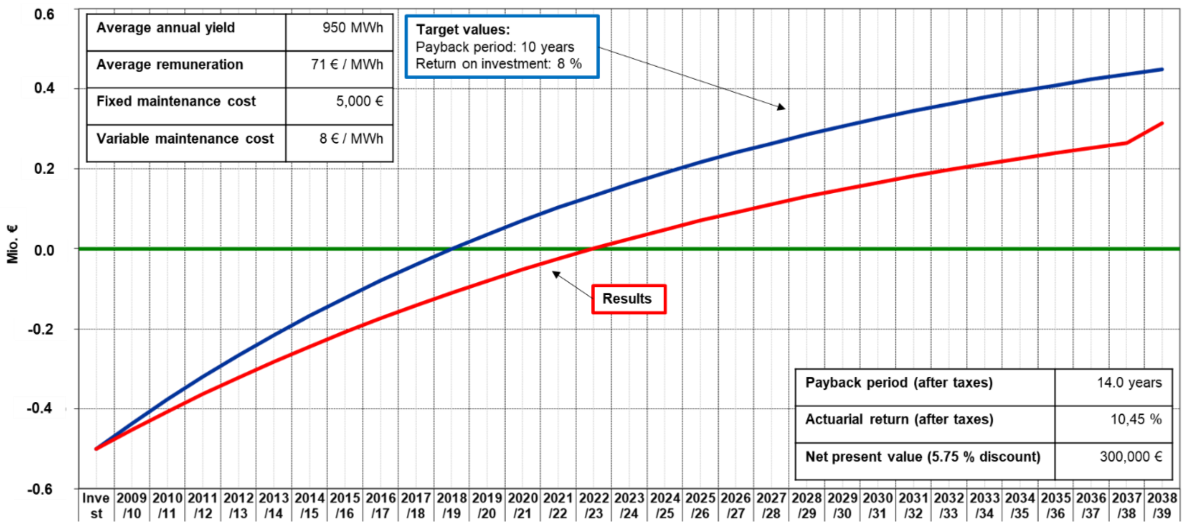


Figure 5-18: Enercon E-40/6.44 – Micro-economic rentability in a 30-year basic scenario

However, prolonging the service life and deploying IAMS technology in combination showed remarkable micro-economic results. In this case study it was assumed that an installation of an IAMS system was able to increase the technical availability and therefore the annual power output by 25 % in combination. Its costs for smaller wind turbine systems were assumed to be 3 € / MWh power output. In this, older and smaller wind turbines can profit tremendously from smart maintenance optimizations. The reference wind turbine performed with an average payback period of 10 years, an actuarial return of 13.2 %, and a net present value of 500,000 €. Figure 5-19 displays the simulation results.

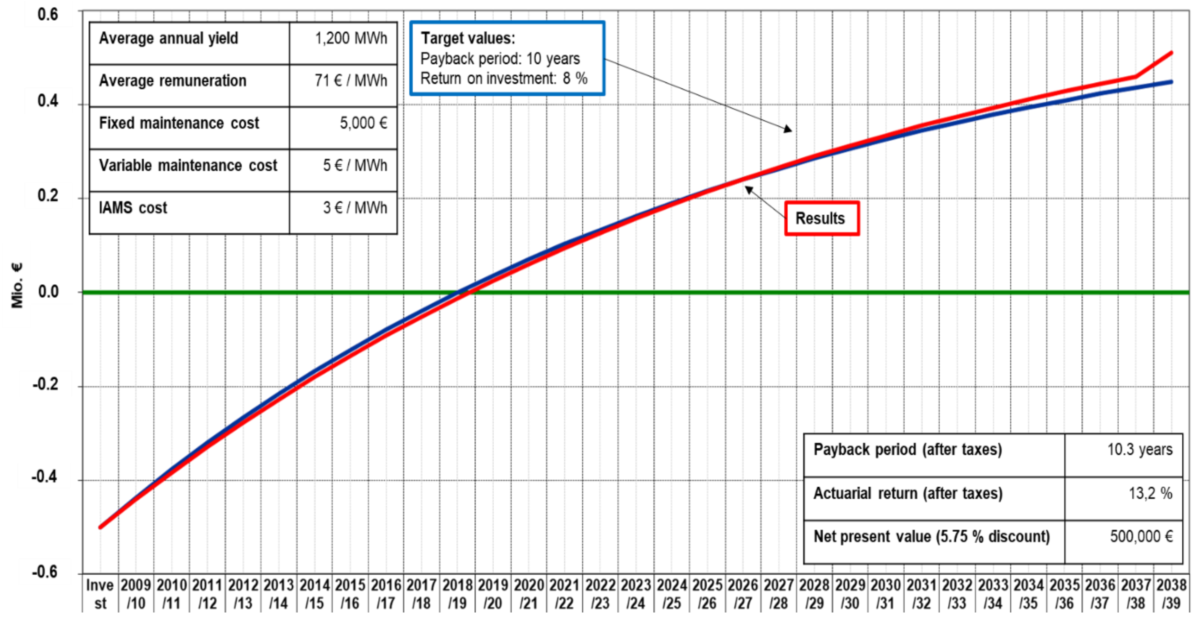


Figure 5-19: Enercon E-40/6.44 – Micro-economic rentability in a 30-year advanced scenario

Concluding it can be stated that positive micro-economic effects of integrated asset management systems from an operators or investment perspective are eminent. However, considering the dissemination of prolonged service life concepts it is recommendable to conduct a detailed rentability analysis of a service life prolongation of the individual wind turbine project with detailed data and a thorough cost assumption of deployed monitoring and inspection techniques, rising maintenance costs, and decreasing energy prices in a competitive energy market outside a feed-in tariff regulation framework.

5.3 Further Aspects of an Integrated Asset Management System

5.3.1 Integration of the IAMS-Concept in an Industrial Environment

In analyzing the industrial potential of the IAMS concept some core findings are detained.

As asset management in many industrial companies is tightly connected with enterprise resource management concepts and systems, asset management methodologies will need to have an active interface with the following fields:

- Work order management
- Resources management
- Spare part management
- Supplier management

Furthermore, the integration and connectivity of mobile devices, operating in one asset management system, with no media disruptions are core.

Additionally, it is important to also analyze, optimize, and adjust all asset management processes within such a framework, to ensure, that all developed aspects can perform as designed.

Finally, and of the greatest importance, industrial implementation of new asset management methodologies will need to focus on asset management staff in strategic positions as well as in operative positions. Knowledge, convictions, and skills will have to be developed in transformation projects in the future. Successful organizational transformation concepts concentrate on the user perspective and implement all innovations with respect to specific change management aspects in the individual situations of the relevant organization (Geiss and Kuhn 2018).

5.3.2 Smart Asset Management Transformation Concept

Looking from an industrial view point, holistic digital asset management concepts – so-called smart asset management concepts - will play a key role in the future to further optimize wind energy systems and the cost of wind energy. Monitoring and inspection techniques and their inter-connectivity to other cyber physical systems in a smart asset management framework will play a key role to leverage further economic potentials in the energy system. Smart asset management concepts will be interconnected with various other information sources to interact in an energy production network. Computer models will be available, representing the complete value chain, from the electric grid, to wind turbine controllers and dynamically determine the operation and maintenance strategy of wind turbine systems. Based on the presented IAMS concept, digital platforms and algorithms can be developed to enable the optimal operation of existing wind turbines in the future – more variable and competitive – energy market. Such concepts can be the data basis for wind turbine controllers to optimize and balance the power output of wind turbines depending on the energy market situation, and dynamically adjust to the market situations. In some situations, it might be optimal to take advantage of a time-of-day price arbitrage and feed power into the grid or operate in a life extending curtailment mode for example. Considering maintenance planning, such information will be relevant in optimizing maintenance time slots and dynamically commissioning servicing activities in time slots in which it is not lucrative or profitable to operate a specific wind turbine system. Therefore, future IAMS concepts will need to be fed with various information to find the globally optimized operations and maintenance decision. That information can be grouped in:

1) Historical operation and maintenance data
2) Asset management planning information (current and future)
3) Available turbine power
4) Remaining useful life of the main components
5) Weather data
6) Energy price data and power remuneration possibilities
7) Availability of spare parts
8) Availability of asset management resources (staff, material, equipment, etc.)

This vision will need a high flexibility of resources and the assurance of seamless information streams. Maintenance instructions, which components need to be inspected, repaired or replaced can be delivered to inter-connected mobile devices for the maintenance staff. However, the technology is already available at a high technology readiness level; the focus in the upcoming years will be on the organizational side, to retrieve existing maintenance data, to develop the suiting process framework in asset management organizations and building acceptance and knowledge on the human resources side. One of the greatest challenges will be to qualify already existing assets and wind turbines for such an inter-connected future framework. Wind turbines in the early 1990s did not even have an internet connection or were connected using narrow banded communication lines. Furthermore, master data structures and maintenance information did not exist. Figure 5-20 describes a transformation concept for existing wind turbines how to qualify for a digital asset management framework. Future research should focus on a detailed technical elaboration of such concepts.

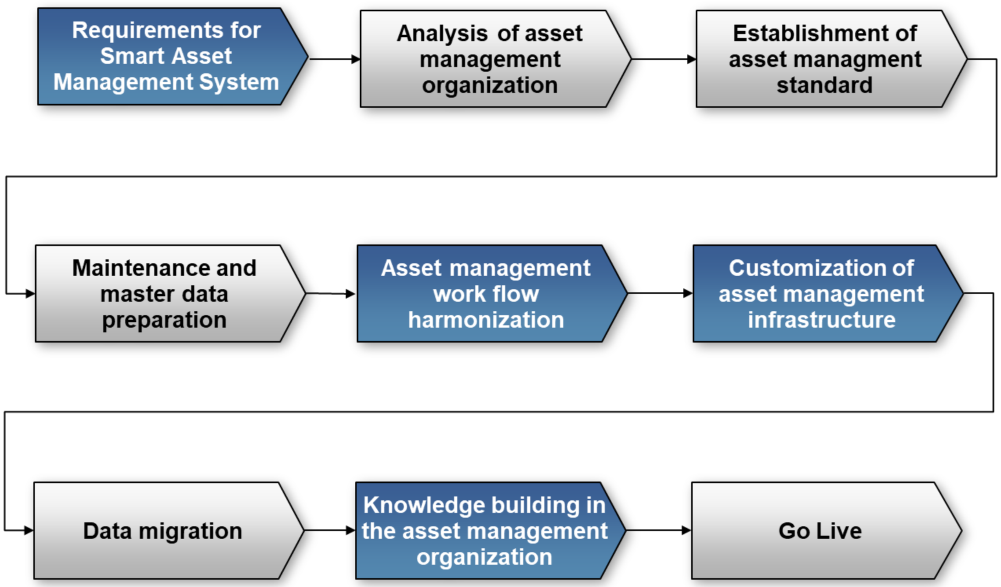


Figure 5-20: Smart asset management transformation concept on an organizational level

Similar to the level of interconnectivity of assets, mobile devices, and cyber physical systems, cyber security concepts and precautions need to be developed and adjusted. This is especially core for assets in the energy systems, as they can be considered cyber critical assets. Considering this line of thought, especially older – analogous SCADA– operation systems bare a high vulnerability when connected to the internet without the relevant protection layers.

Lastly it is clear that these described operation and maintenance data sources are key for future business models for operators, manufactures, and service providers. Data-as-a-service concepts will be one of the future pillars in asset management and after-sales business models of many market players. Traditional market players already recognized this potential and secured their market position with the relevant patent rights, which at the same time hinders or blocks the market entry of smaller companies. However, flexibility and agility will be core for future digital business models in asset management of renewable energy systems of the future.

5.3.3 CODA WAVE INTERFEROMETRY AS DETERIORATION CONTROL TECHNIQUE

As described in chapter 4.5.8 coda wave interferometry-based ultra sound inspection techniques bare great potential for suitable deterioration control techniques of wind turbine supporting structures build in concrete in the future. Considering future research, especially in-field test situations need to be analyzed, with the goal of developing robust testing methods, which can be applied in practical situations. Therefore, novel algorithms need to be developed to filter various in-field effects. Furthermore, the practical suitability of coda wave interferometry-based techniques will mainly depend on the possibility to calibrate and quantify the ultrasound data to the damage evolution process of the respective materials under wearing conditions. Based on this, imaging techniques will help asset management engineers to interpret the testing results of arbitrary structures in field. To foster the development, simulation methodologies of NDT experiments can help to understand effects of specific damage or fatigue scenarios of wind turbine supporting structures on the wave propagation physics. However, simulations must also be matched with controllable laboratory investigations, in which the single parameter influences can be tested and understood. Considering the special test case of wind turbine supporting structures, a future research aim should also be to developed guideline recommendations of sensor arrangements and test set-ups in field. Lastly for future wind turbine structures the deployment of in-situ sensor technology can be relevant for an optimized life cycle management data base, when it comes to information of the degradation state of certain parts in a wind turbine structure.

5.3.4 INTEGRATION OF EMPIRICAL DATABASES

Asset management of wind turbine systems will significantly benefit from industry-specific empirical databases in future. The Wind-Pool project has been trying to set such a benchmark since 2013. The original objective of Wind-Pool - comparable to the OREDA offshore data base described in chapter 3.3.2 - is the collection of reliability data of equipment and systems in wind industry. In future, Wind-Pool should cover a wide range of reliability data from equipment used in the onshore wind branch. Hereby, it is core to apply a defined reference designation system to clearly identify the specific components. The primary goal of the database project is to contribute to enhanced safety and cost-effectiveness in operation and maintenance activities and to further reduce the LCOE of wind energy. Systematic data collection and analysis of O&M data is a fundamental task, establishing a high reliability, availability, and safety standard among the industry. Currently, 2000 wind turbine systems – from twelve different OEMS - report their reliability data anonymously to the platform. In future such platforms will have to merge to industry standards which finance themselves and are not dependent on state subventions (Fraunhofer Institut für Windenergie und Energiesystemtechnik 2018).

5.3.5 IMPROVING WIND TURBINE TOWER STRUCTURES WITH UHPFRC

UHPFRC is an advanced cementitious-based material, its specific material properties can be modified by the special recipe and casting process. The mechanical material properties of UHPFRC are outstanding: compressive strength > 170 MPa, uniaxial tensile strength > 8 MPa, flexural strength > 30 MPa. UHPFRC can be assigned to the group of high performance reinforced cementitious composites. Figure 5-21 compares the uniaxial tensile strength behavior of UHPFRC, steel fiber reinforced concrete (SRC), and conventional concrete. The significantly high tensile strength and the strain-hardening behavior of UHPFRC are characteristic for its value to rehabilitation application of existing wind turbine structures.

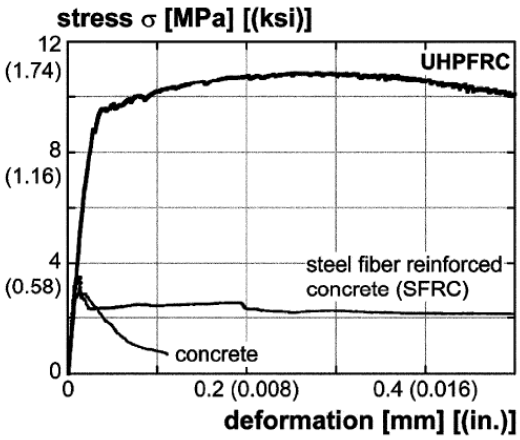


Figure 5-21: Uniaxial tensile strength of UHPFRC, SFRC and concrete (Habel 2004)

Extensive service life prolongation programs will be in need of smart, safe, and cost-effective retrofit and rehabilitation solutions to maintain and optimize existing wind turbine structures. UHPFRC can increase the serviceability and durability of existing wind turbine structures on- and offshore to a new level. Especially the rehabilitation of existing structures with UHPFRC is a promising approach when it comes to safe and sustainable service life prolongations of wind turbine structures. Many wind turbine structures will suffer from combined effects of freeze-thaw cycles, aggressive environments, and high fatigue loads.

For this, UHPFRC bares various advantages: the material can be easily cast on-site due to its practical rheological and self-compacting properties, UHPFRC shows an extremely low permeability for damaging environmental substances and shows a very high durability which would improve existing wind turbine structures. Furthermore, the rapid strength gain of UHPFRC is also advantageous. UHPFRC material can gain a compressive strength of > 80

MPa a day after casting. The long-term durability guarantees a minimized number of interventions and avoids multiple rehabilitation efforts for existing structures (Brühwiler and Denariè 2008; Denariè and Brühwiler 2006). Known disadvantages of UHPFRC are the comparatively high material and manufacturing cost and the current lack of standard designs.

A future rehabilitation concept for existing wind turbine structures will have to focus on exposed structural zones which are under high loading and severe environmental conditions. Other parts of the wind turbine structure can remain in their original design.

However, a profound understanding of the material behavior in cured and uncured states will be core for future rehabilitation concepts of wind turbine structures. Especially in focus is the dimensional behavior relative to the substrate. Relative dimensional stresses lead to internal stresses and result in preliminary fractures in both the substrate and the repair material. Loss of load bearing capacity, delamination, or early deterioration may be the consequences.

Since the early 2000s various examples of practical applications of UHPFRC as structural rehabilitating material have been shown. First applications mainly focused on the rehabilitation of bridge constructions and showed that rehabilitation concepts of structural systems can be significantly more sustainable and less environmentally intruding then new constructions. Such rehabilitation projects have so far been conducted in Sweden, Switzerland, Slovenia, and Canada, particularly to mention are the works of Brühwiler and its team at EPFL-MCS (e.g. Denariè 2018; Denariè and Brühwiler 2006; Brühwiler and Denariè 2008; Habel 2004).

Thus, rehabilitation concepts for wind turbine structures can be inspired from past and current rehabilitation and reinforcement concepts with UHPFRC for bridge structures.

Principally a reinforcement strategy for wind turbine supporting structures applying UHPFRC should pursue two main objectives:

1) Strengthen the lower part of the tower, which is subject to high tower base bending moments
2) Seal the connection between tower and fundament structure to prevent water penetration and the penetration of corrosive or damaging substances

Denarié describes a showcase which can be the basis for wind turbine supporting structure reinforcement and service life prolongation and focusses on a turret in the Lorient bay in Brittany, France. The “service life” of the turret is already approximately 70 years (Denariè 2018). Figure 5-22 displays the concepts of Brühwiler and Denariè for road bridges and light house reinforcements with UHPFRC, which could be the basis to derive a practical concept for wind turbine supporting structure reinforcement and rehabilitation concept in future (Denariè 2018).

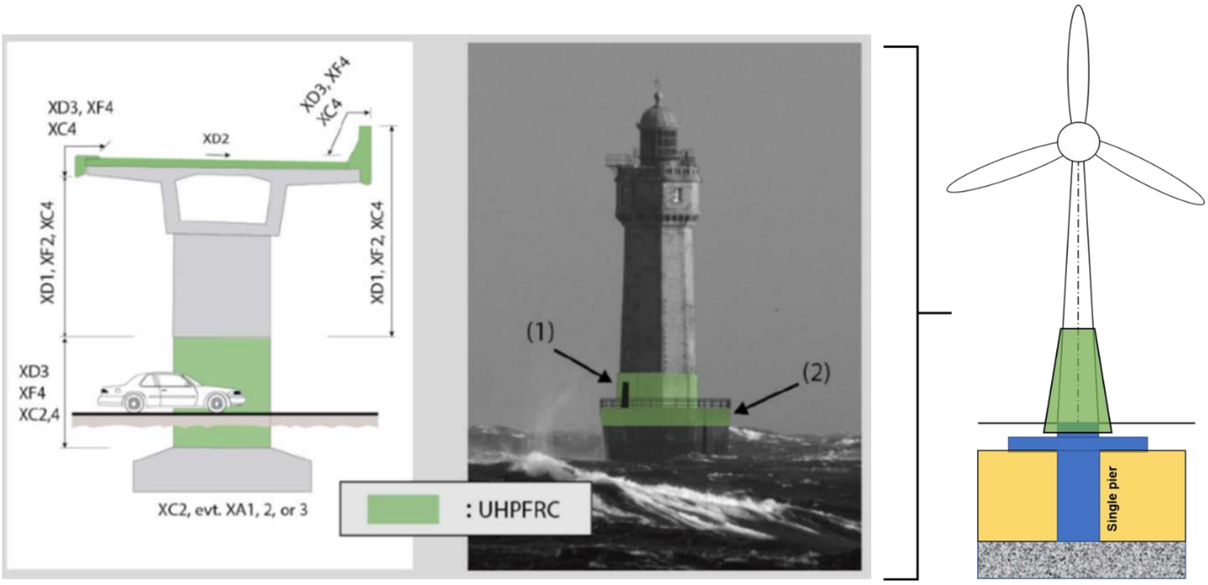


Figure 5-22: Future rehabilitation concept for wind turbine supporting structures – adapted from (Denariè 2018)

Furthermore, it might also be worthwhile and cost-effective in the long-run to consider UHPFRC for the design of wind turbine structures. Various studies and designs already exist (Sritharan 2013; Nazar 2014).

Finally, the INFRASTAR-project has to be mentioned. The focus of the project is on the prediction of concrete infrastructure behavior under fatigue. INFRASTAR considers two representative types of concrete infrastructures: bridges and wind turbine towers and foundations (IFSTTAR - French institute of science and technology for transport, development and networks 2018).

5.3.6 RECYCLING OPTIONS FOR WIND TURBINE SYSTEMS

If the economic analysis opts against a prolonged service life concept or if wind turbine systems have reached their maximum technological and economical service life, innovative and sustainable recycling technologies should take over in the last life cycle phase of a wind turbine system as described in Figure 4-2.

Currently about 80 to 90 % of a wind turbine system is recyclable. Especially for the supporting structure (steel and concrete), nacelle, gearbox and hub (steel), as well as all electrical components (copper) there are established and economical recycling methods (Berkhout and Faulstich 2014). Adequate and economic recycling technologies for rotor blades are currently under investigation and face various obstacles. Generally, there are four main disinvestment and recycling strategies for wind turbine systems:

1) Depositing
2) Combustion
3) Recycling
4) Second-hand sale

First, depositing of GFRP materials was forced in Europe, however some EU member states forbad landfills for GFRP materials (Holmes 2014). Therefore, the combusting of worn-out rotor blades is currently favored. However, due to the low recycling value combustion technologies should only be transitional solutions to reusing GFRP materials from rotor blades. GFRP ash can inherit many harmful substances which require further treatment or special depositing sites. Short glass-fibers can block electrostatic precipitators in combusting plants. Finally, the energy balance of combustion processes is generally low and GFRP only bares a low calorific value of 20 MJ/kg (Yang et al. 2011). More valuable recycling and upcycling technologies are to be developed in future, because of two main reasons: the high employment of primary energy in the manufacturing processes and the upcoming of economic secondary use scenarios for short-fibred materials. A future driving force for more efficient recycling technologies will be the quantity structures of GFRP and CFRP wind turbine rotor blades in the recycling market, the commodity price of recycled fibers, and the future legal framework in Europe in this area. Approximately 40 % of the overall weight of a wind turbine rotor is represented by GFRP material. The GFRP ratio is about 10 kg GFRP / kW installed wind capacity. Industry forecasts presume global GFRP material quantities of about 225,000 tons of recyclable rotor blades in 2035. Figure 5-23 gives an overview of GFRP recycling technologies.

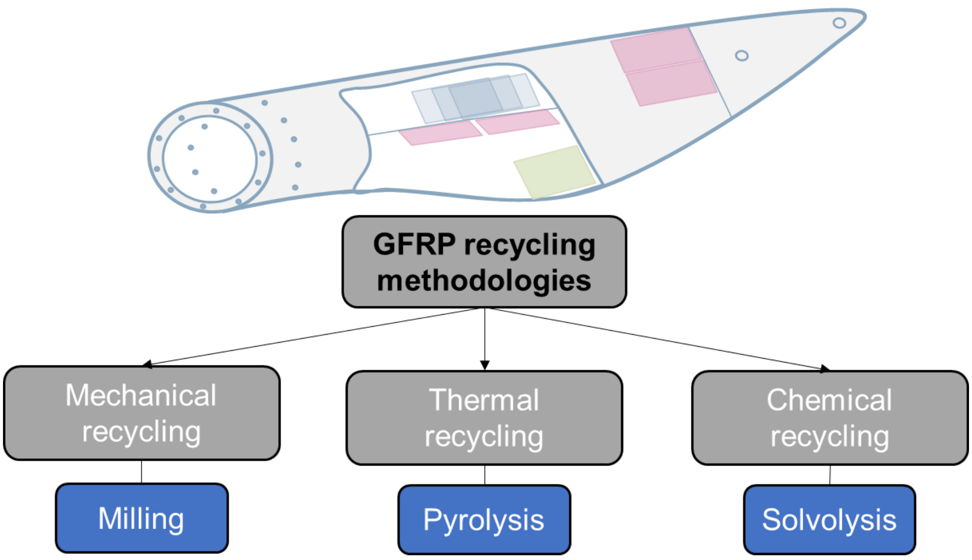


Figure 5-23: Overview of GFRP recycling technology families

One of the more valuable recycling strategies of recycled GFRP fibers is to add these to cement recipes, which was already conducted in Germany (Bloomberg 2018). More advanced recycling methodologies are pyrolysis and solvolysis. However the price of GFRP materials so far does not match the technology cost of these concepts and the mechanical characteristics of the recycled fibers do not match the expected requirements (Oliveux and Dandy 2015). A comprehensive technology and market analysis of recycling possibilities of fiber reinforced material from wind turbine systems can be found in Kuckuck (2015).

6 CONCLUSION

In the future market environment of renewable energy sources – especially for onshore wind energy systems – economic and cost-effective operation will play a key role. This prognosis is valid both for macro and micro-economic frameworks, e.g. for the global environment as well as for the single wind turbine operator. One of the biggest challenges in energy and macro-economic politics will be to steer through the tension field of energy transition from fossil and nuclear sources to renewable energy sources, while at the same time sustaining international competitiveness in the cost of production and ensuring a reasonable reliability level of the systems. The application of condition monitoring and nondestructive testing techniques within an integrated and holistic asset management approach can significantly contribute to this.

The thesis showed how nondestructive testing and structural health monitoring techniques can be applied to establish new efficient and sustainable maintenance strategies for wind turbine systems in a holistic asset management framework.

The conclusion is structured along the main research questions (RQ) of this thesis:

- **RQ 1:** *Which overall macro and micro-economic role and importance can a holistic asset management concept for wind turbines have in the energy transition process?*

To optimize the cost-yield ratio of wind energy from an operator's view, increasing the annual power output by reducing unplanned maintenance downtimes, lengthening the service life of the wind turbine while retaining a reasonable reliability level, and reducing the overall maintenance and repair cost are the main levers.

The key concept from a macro-economic standpoint should be to reduce the levelized cost of energy (LCOE) of wind energy.

The annual energy yield is dependent on the specific turbine characteristics as well as the location characteristics. Derived from technical and mathematical relationships in order to optimize and reduce the levelized cost of energy of wind turbine technologies, three main strategies connected with asset management systems for wind turbines can be clarified:

1) Lower O&M costs

2) Increase power output

3) Increase the lifetime of wind turbines

In chapter 5.2, a generic sensitivity analysis was conducted. The biggest effect IAMS concepts were found to have on LCOE is avoiding unplanned downtimes, in combination with service life extensions.

Furthermore, it was found that service life extension programs in the overall energy system could additionally lead to more sustainability and contribute to the climate saving goals in the framework of the Paris Agreement. The additional possible wind capacity summed up to 26 GW in 2030 for Germany. Lifetime enhancement of wind turbine systems led to additional clean energy in the overall energy system and thus to additional reduction of GHG emissions.

The German GHG emission reduction goal was found to profit from 9.304 Mt CO_{2e} additional emission reductions until 2030 and 1.515 Mt CO_{2e} until 2020.

Lastly, chapter 5.2 showed micro-economic effects an IAMS concept can have in three case studies. All three case studies used a default 20-year basic scenario as reference to evaluate the rentability effects of investing in monitoring and inspection technology to optimize operations.

The 30-year operational scenario for wind turbine B (*MISTRALWIND* test turbine) in which the operator actively focused on avoiding additional maintenance cost and aimed at optimizing the availability of the wind turbine with optimal deployment of monitoring and inspection techniques was found to be most beneficial. The operational optimizations led to maximized micro-economic results, with a payback period of 13.8 years and a net present value of 3 400 000 €, which is 17 % above the basic 30-year service life scenario and 48 % above the current 20-year service life basic scenario.

Concluding, it can be stated that positive micro-economic effects of integrated asset management systems from an operator or investment perspective are eminent. However, considering the dissemination of prolonged service life concepts it is recommendable to conduct a detailed rentability analysis of a service life prolongation of the individual wind turbine project with detailed data and a thorough cost assumption of deployed monitoring and inspection techniques, rising maintenance cost, and decreasing energy prices in a competitive energy market outside a feed-in tariff regulation framework.

- **RQ 2:** *What is the status quo in wind turbine asset management and which requirements can be considered for a holistic asset management concept?*

The wind energy industry has not yet achieved an integrative asset management framework. One of the main deficits are the missing systematics in the overall asset management goal on a strategic and operative level, in finding the optimal maintenance and spare part strategy, the maintenance process itself, the maintenance documentation, and data analysis – to name a few. The current data availability and data quality are low. There is no consistent information structure. A uniform incident classification system throughout the wind industry is not state of the art, therefore operational and maintenance incidents cannot be described one-to-one. Thus, the description of failure modes, root causes, and subsequent failures is biased, and logical conclusion and historical analysis for a sustainable system knowledge to prevent severe failures is only possible to a limited extent. Lifetime documentation of wind turbines is incomplete and fragmentary, not digitalized and sometimes non-existent. If any data is available, technical incident data and the resulting operation and maintenance cost data are acquired and stored in different systems with no logical connection. Consequently, it is extremely difficult and extensive to carry out comprehensive maintenance analysis studies. Considering maintenance software and computerized maintenance management systems (CMMS), proprietary and isolated software solutions inhibit integrative and holistic views on complex maintenance problems. General integrative standards are missing or in stage of development and not ready for broad industry application. Furthermore, the communication between all persons involved in the operation and maintenance activities of wind turbines needs to be improved.

A major future topic will be lifetime extension programs of wind turbines reaching the end of their original design life, carrying considerable structural wear reserves which need to be used for a more sustainable and economical operation of wind turbine systems.

For most of the existing turbines the original design documentation will not be available to the operators. Therefore, simplified approaches using data available to the operators – such as SCADA data – have to play a key role in an integrated asset management framework. The implied application of generic and deterministic engineering models needs a consideration of the respective uncertainty. Load measurements with structural health and condition monitoring sensor systems as well as nondestructive inspection techniques should be included additionally to reduce model uncertainties. A turbine-specific inspection program considering scope and intervals must be developed based on the calculation results. Furthermore, the following information must be taken into consideration as part of the assessment:

- Operational history
- Maintenance history
- Reports from inspections
- Failure reports / reports on extraordinary maintenance activities
- Documentation on exchange of components
- Documentation on changed controller settings
- Field experience with turbine type
- Based on the probabilistic approach, risk-based inspection methods may be developed.

All available information to the operators has to be integrated in an operational data base management system, logically linking and storing all different data streams.

A core element of a future integrative asset management system for wind turbines must be a holistic operational data base management system, which integrates all data streams relevant for wind turbine operation and management activities of each life cycle phase.

- **RQ 3**: *Which sub-systems of a wind turbine system induce the most risk potential from an asset management view point?*

Considering the annual failure rate as an equivalent for the occurrence probability of specific failure modes in the wind turbine sub-systems, it can clearly be derived that among the rotor hub, generator, transformer, rotor blades and gearbox, the turbine supporting structure is one of the most critical sub systems.

The provisional result of a risk analysis applying a classic FMEA analysis lead to the conclusion that tower, gearbox, rotor blades, main bearing, and generator are the most critical systems for which a condition-based maintenance strategy might be most accurate.

However, all classic risk analysis approaches based on FMEA showed critical weaknesses. First and foremost, the relative importance between the three parameters is not considered. Furthermore, different combinations of parameters may lead to the same risk-priority number, however hidden risk implications can be entirely different. Also, important interdependencies among various failure modes and effects are not considered.

Considering the weaknesses of the traditional FMEA methodology used to analyze operating wind turbine systems to establish risk-based maintenance strategies, a new holistic approach to evaluate systematic risks in a wind turbine system as a first quantitative step in finding the optimal maintenance strategy was introduced. The cost-based risk analysis (CBRA) focused mainly on the cost consequences of a failure, which also represents the primary concern of wind turbine operators considering operational risks.

In comparison to the results of the FMEA analysis in chapter 4.3.2 the cost-based risk analysis results were more differentiated according to their cost perspective. For both the onshore and offshore wind turbine systems, the supporting structure was clearly exposed as the most critical sub-system when it comes to cost consequences.

- **RQ 4**: *What can a qualitative maintenance strategy decision framework look like?*

Based on the described qualitative risk analysis, chapter 4.4 introduced a specific service strategy decision procedure on a qualitative level. The first step was to define the asset system functions in their operating context. Conceptually, there are two categories. Primary functions describe the primary goal of the asset's existence, e.g. to convert kinetic wind energy into electrical energy. Secondary functions describe requirements of the asset concerning safety, control, structural integrity, economy, efficiency of operation, and compliance with regulations.

The turbine system was subdivided in its primary and secondary functions. Based on this level, all relevant failure modes of the involved sub-systems and parts were deducted. The next level of analysis considered all relevant failure causes of every deducted failure mode. Subsequently, the respective failure modes were evaluated concerning their induced failure consequences. According to the applied risk evaluation scheme, risk mitigation tasks were to be defined. Based on the failure cause level of each failure mode, one could derive suitable monitoring and inspection tasks, which could detect the relevant failure cause early and enable the maintenance engineers to derive preventive measures.

The two most relevant deterioration mechanisms for a wind turbine supporting structure are corrosion mechanisms and wear or fatigue crack growth mechanisms. Considering normal environmental conditions and a reasonable implementation of corrosion protection, the wear mechanisms are the most critical deterioration mechanisms of the structural system.

- **RQ 5**: *Which damage detection and data analysis techniques are most suitable for a holistic asset management concept for wind turbines?*

One core part of the IAMS-concept is a holistic damage detection database which was developed in the scope of the dissertation and is the result of an extensive research in the field. The database is programmed in MS Excel and uses VBA-code for data analysis. However, the database can also be connected or integrated into a CMMS system. Chapter 4.5 reviewed the most relevant damage detection techniques to be applied in a practical monitoring and inspection framework of wind turbine systems.

Figure 4-32 shows the recommended allocation of relevant asset management key performance indicators for the MISTRALWIND test turbine on a sub-system level. Which monitoring technique is applied to analyze the KPIs is mainly cost-driven and can be evaluated individually in the framework of the holistic damage detection database framework.

- **RQ 6:** *How should a holistic and integrated asset management concept for wind turbines be designed?*

The technologic core of the IAMS-Wind concept is based on a multilevel condition and structural health monitoring concept which can be seen as a new and innovative approach to life cycle management for wind turbines. The approach is in no need of complicated and computationally intensive aeroelastic simulation models. The concept combines monitoring and inspection data holistically. Thus, the condition assessment can be done based on the real component loading and is not solely dependent on load simulations and model site parameters, which can bear huge uncertainties.

The approach consists of three monitoring levels, for which the monitoring scope but also the cost and effort increase from one level to the next. Monitoring level 1 is concerned with load monitoring using standard operating signals from the wind turbine's SCADA system. Chapter 4.6.1 introduced a methodology which in three basic modules for rotor blade, drive train, and supporting structure system enables operators to conduct a fast fatigue check to analyze the consumed service life of the main components on a load monitoring basis. For older turbines, SCADA-load monitoring in level 1 might be the only economically possible option to conduct condition or structural health monitoring. For most wind turbines, however, monitoring level 1 will not be accurate enough to predict a possible remaining useful service life and detect and predict damages in the system. Therefore, monitoring level 1 is consecutively combined with monitoring level 2 for structural health and condition monitoring with separate sensor system and monitoring level 3 for updating monitoring data with nondestructive testing results from damage hot spots in the field. The claim to design a holistic monitoring and inspection approach implies the combination of monitoring data and inspection data. Condition and structural health monitoring can only be considered holistic if it combines indirect load monitoring, standard signals, and separately installed system and in-field inspections. The choice of monitoring level is mainly driven by the optimal relationship between monitoring effort and cost, and the resulting cost benefits or safety reduction benefits for the operator. This decision can be supported by a risk and profitability analysis as conducted in chapter 4.3. However, in practice, such a quantifying analysis can also lead to the conclusion that none of the monitoring or inspection effort would overrule safety or profitability issues.

Monitoring level 3 seeks to combine monitoring information, which is mainly based on fatigue design laws, with actual in-field information retrieved with nondestructive testing techniques to update the actual remaining useful service life resources. Aiming on this goal the concept of risk-based inspection planning, combining the assumptions of structural reliability analysis and Bayesian updating promises to provide the appropriate instruments and tools, therefore. Currently it is unclear how long a remaining useful service life can be in the damage tolerant mode beyond 20 years, because no empirical data exists so far.

- **RQ 7:** *Is it possible to establish relations between SCADA-data and load measurements for wind turbine fatigue monitoring?*

In theory, there are various suitable analysis techniques for the set-up of a load monitoring fed with SCADA-data signals. Detailed physical models are not suitable because they require a lot of detailed structural and geometrical information which is not available to every wind turbine operator in practice. Furthermore, detailed models imply the necessity of high-resolution time series. However, SCADA-data is normally delivered at a sampling frequency of 0.001 Hz. Applying regression techniques bares the advantage that such models do not need detailed structural information of the turbine, however, regression models are not able to reproduce the non-linear behavior of the turbine structure. Separate regression models would be necessary for each load bearing component of interest, which in turn would result in a high amount of manual work setting up the regression models. Another possible data analysis technique for SCADA-signals would be state-observers or the application of ANNs. Both approaches need a suitable pattern recognition system to predict all transient events and non-linear behaviors of the wind turbine structure. Both approaches stand or fall with accurate training data of the wind turbine behavior in all relevant load cases and situations at the specific site. In practice, this circumstance cannot be guaranteed. Therefore, both models were evaluated to be not suitable for a practical on-condition load counting procedure to track remaining useful lifetime reserves but might be suitable for more sophisticated and detailed load design analysis based on SCADA-data.

Simplified engineering load transfer models showed to be most suitable for an online fast fatigue check (*FATIWIND*). In the scope of the dissertation, three basic modules were developed for the wind turbine's main load bearing and transferring components: rotor, drive-train, and tower.

If specific site information is not available it is also suitable to deploy general data from the IEC site classifications, which are publicly available. Due to the fact that the fatigue limit state information does not consider individual site-specific information, the approach deploying IEC site classification data is more conservative.

- **RQ 8:** *Which concept is suitable to combine monitoring and inspection techniques in one holistic approach?*

The concept of risk-based inspection planning inherits the primary goal of quantifying the effect of inspections on the risk condition of a component and thus enables cost optimal inspection planning, Therefore, it was found to be most suitable to combine monitoring and inspection data in a holistic asset management framework. Given the fact that design deterioration laws represent unperfect knowledge considering the component's deterioration process in service, risk-based inspection planning is a suitable method for deterioration control under in-service conditions.

The concept of risk-based inspection strategies is defined as monitoring level 3 and completes the multi-level monitoring concept introduced in chapter 4.6. Furthermore, the methods presented here can be used as implementation guideline for the probabilistic approach to determine the remaining useful lifetime of wind turbine systems, as defined in the DNVGL guidelines for service life extension of wind turbines introduced in chapter 2.4.3.

The approach combines Bayesian decision analysis with structural reliability analysis. Available probabilistic models of the deterioration process and the inspection performance are used to present a consistent decision basis. Deterioration processes of structures are of highly stochastic nature. Models describing these processes involve large variations and uncertainties.

Ultimately, the decision analysis process aims for the identification of optimal decisions on maintenance actions for deteriorating structures. The decision environment is subjected to uncertainty under the following aspects:

- Uncertainty on the state of the system; state of deterioration
- Uncertainty on the performance of the inspection; probability of detection (POD)
- Uncertainty on the performance of repair actions
- Uncertainty on the consequences of failures

The decision problem is summarized in a decision tree. Each path of the decision tree is assigned a utility value and its probability characteristics.

- **RQ 9:** *Which data management concept is most suitable for a wind turbine life cycle file?*

The core focus of a holistic operational data base management system (ODBMS) for asset management purposes is the integration of information over the whole life cycle of assets and interdisciplinary cooperation and communication of data. Therefore, a horizontal (different life cycle phases, contractor, OEM, operator) as well as a vertical integration (actuator, sensor, control level management level) of its systems needs to be realized.

A modern ODBMS should be post-relational with no need for entity relationship models to be compatible with big data analytics, IoT-technology, and to run predictive analytics to its best performance. In an integrated asset management system, a main task is remote monitoring and diagnostics of many sub-systems and components. The process of gathering data relevant to the analysis tasks is most time consuming in many cases. Ontology-based data models are semantically rich conceptual domain models and can support service engineers in their data analysis tasks, because ontologies describe the domain of interest on a higher level of abstraction in a clear manner. Therefore, an ontology-based data management framework was found to be the most-suitable concept to implement a wind turbine life cycle file (LCF).

Considering a minimum data collection level to operate an ODBMS in a proper way, one can define the following minimum data collection requirements:

- Master data
  - Explicit plant identification
  - Designation of plant type
  - Date of commissioning
  - Beginning of data collection
  - Site location (longitude, latitude)
- Operational data
  - Wind speed (min, max, mean, std)

    - Wind direction (min, max, mean, std)
    - Plant power (min, max, mean, std)
- Incident data
    - Explicit and unique designation of event
    - Wind farm ID
    - Wind turbine ID
    - Time stamp of event
    - Time stamp of maintenance task conclusion
    - Functional state of wind turbine according to ZEUS block 01-02; at least to be categorized into “turbine not operational” or “turbine operational”
    - Type of event which caused the functional wind turbine state according to ZEUS block 01-04
- Component data per event
    - Explicit and unique designation of concerned component according to RDS-PP
    - Failure cause according to ZEUS block 02-05
    - Maintenance type according to ZEUS block 02-08
    - Maintenance measure according to ZEUS block 02-09
- Additional information (if available)
    - Functional state of element according to ZEUS block 02-01
    - Detection possibility according to ZEUS block 02-02
    - Detection symptoms according to ZEUS block 02-03
    - Failure mode according to ZEUS block 02-04
    - Failure consequences according to ZEUS block 02-06
    - Responsible person according to ZEUS block 02-10
    - Deviation of certified condition of wind turbine according to ZEUS-block 02-12
    - Replaced components and parts
    - Deployed materials
- Cost data
    - Overall maintenance cost per wind turbine and year
        - Fixed maintenance cost (service contracts)
        - Other fixed maintenance cost
        - Variable maintenance cost
        - Other cost
    - Economic maintenance performance data
        - Cost per event
            - Logistic cost
            - Spare part cost
            - Etc.

At large, the thesis has shown, that it is possible to design a holistic asset management system for wind turbines, taking into account all relevant aspects. The IAMS concept can pave the way for a more sustainable operation of wind turbine systems in future and can be seen as a contribution to the energy transition process in the upcoming years.

Everything will be alright in the end. If it's not alright, it's not the end …

Oscar Wilde (among others).

IX. LITERATURE

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X. STANDARDS AND GUIDELINES

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DNVGL-SE-0074: 2018– Type and component certification of wind turbines according to IEC 61400-22.

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XI. ANNEX A: PARIS AGREEMENT

"Article 2

1. This Agreement, in enhancing the implementation of the Convention, including its objective, aims to strengthen the global response to the threat of climate change, in the context of sustainable development and efforts to eradicate poverty, including by:

(a) Holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1,5 °C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change;

(b) Increasing the ability to adapt to the adverse impacts of climate change and foster climate resilience and low greenhouse gas emission development, in a manner that does not threaten food production;

(c) Making finance flows consistent with a pathway towards low greenhouse gas emissions and climate resilient development

2. This Agreement will be implemented to reflect equity and the principle of common but differentiated responsibilities and respective capabilities, in the light of different national circumstances."

"Article 4

1. In order to achieve the long-term temperature goal set out in Article 2, Parties aim to reach global peaking of greenhouse gas emissions as soon as possible, recognizing that peaking will take longer for developing country Parties, and to undertake rapid reductions thereafter in accordance with best available science, so as to achieve a balance between anthropogenic emissions by sources and removals by sink of greenhouse gases in the second half of this century, on the basis of equity, and in the context of sustainable development and efforts to eradicate poverty"

4. Developed country Parties shall continue taking the lead by undertaking economy-wide absolute emission reduction targets. Developing country Parties should continue enhancing their mitigation efforts, and are encouraged to move over time towards economy-wide emission reduction or limitations targets in the light of different national circumstances."

"Article 13

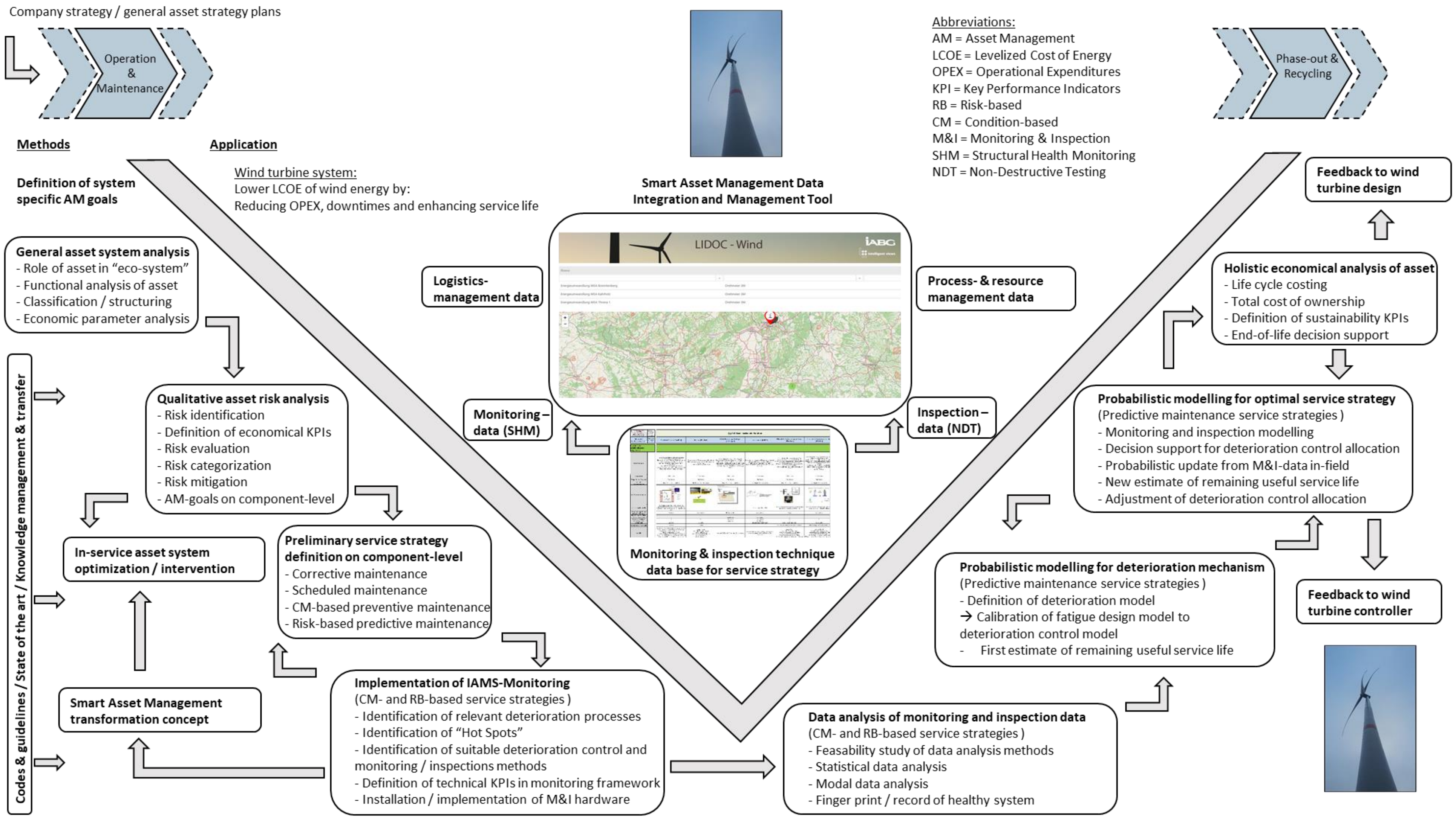
7. Each Party shall regularly provide the following information:

(a) A national inventory report of anthropogenic emissions by sources and removals by sinks of greenhouse gases, prepared using good practice methodologies accepted by the Intergovernmental Panel on Climate Change and agreed upon by the Conference of the Parties serving as the meeting of the Parties to the Paris Agreement;

(b) Information necessary to track progress made in implementing and achieving its nationally determined contribution under Article 4."

"DONE at Paris this twelfth day of December two thousand and fifteen."

XII. ANNEX B: INTEGRATED ASSET MANAGEMENT SYSTEM FOR WIND TURBINES



XIII. GLOSSARY

***Albert Betz** (1885 – 1968)*	Albert Betz was a German physicist and aerospace engineer. He developed some important today's basics in aerodynamics and wind energy.
Bora	Cool down-wind system at the Adriatic coast.
Coriolis-force	Coriolis forces appear in rotating reference systems, if masses in the reference system move in relation to the reference system. The force is named after Gaspard Gustav de *CORIOLIS* (1792 – 1843).
Design life	Period that was considered for the strength verification when the device was designed.
Ekman-Layer	The Ekman layer is the layer in a fluid where there is a force balance between pressure gradient force, Coriolis force and turbulent drag. It was first described by Vagn Walfrid Ekman. Ekman layers occur both in the atmosphere and in the ocean.
Foehn	Warm down-wind system in the Alpine region.
GtCO2e	GtCO2e is an abbreviation for "gigatonnes of equivalent carbon dioxide". A gigatonne is a thousand million tonnes. It is a simplified way to put emissions of various GHGs on a common footing by expressing them in terms of the amount of carbon dioxide that would have the same global warming effect.
Johannes Juul (1887 – 1969)	Johannes Juul was a Danish engineer who is remembered for the important part he played in the development of wind turbines.
Lifetime extension	Additional lifetime beyond the design lifetime.
MISTRALWIND – Monitoring and Inspection of Structures at Large Wind Turbines	Funded research project by the Federal Ministry for Economic Affairs and Energy carried out in the period from 2015 to 2018 with IABG as consortium leader and Technical University Munich, Siemens AG and Max Bögl Wind AG as research partners.
Paul LaCour (1846 – 1908)	Poul la Cour was a Danish scientist, inventor and educationalist. Today la Cour is especially recognized for his early work on wind power, both experimental work on aerodynamics and practical implementation of wind power plants.

	He worked most of his life at Askov Folk High School where he developed the historic genetic method of teaching the sciences. Early in his life he was a telegraphic inventor working with multiplex telegraphy. He developed the first wind turbine system using electrolysis to store wind energy in hydrogen gas.
Prandtl-layer	In 1904, Ludwig Prandtl, the well-known German scientist, introduced the concept of boundary layer and derived the equations for boundary layer flow by correct reduction of Navier-Stokes equations. He hypothesized that for fluids having relatively small viscosity, the effect of internal friction in the fluid is significant only in a narrow region surrounding solid boundaries or bodies over which the fluid flows.
Rainflow counting	The rainflow counting algorithm is used to convert a spectrum of varying stresses into a simple set of stress reversals. The algorithm was developed by Endo and Matsuishi in 1968. The name is derived from a graphical explanation example, in which rain is flowing down a pagoda shaped roof.
Rüdiger Rackwitz *(1968 – 2008)*	Prof. Rüdiger Rackwitz was an outstanding scientist and engineer, who initiated and developed many of the state-of-the-art methods in structural reliability and risk assessment for civil engineering systems. He pioneered many practical applications and was pivotal in implementing modern safety concepts in the Eurocode.Prof. Rackwitz is one of the most respected scholars in our field due to his many scientific achievements as well as his visionary ideas, which have inspired and shaped many of the leading figures in the reliability and risk community.
Service life	Lifetime from commissioning to decommissioning of a component or wind turbine system.
Thomas Bayes *(1701 – 1761)*	Thomas Bayes wan a statistician, philosopher and Presbyterian Minister. Bayes' solution to a problem of inverse probability – which is nowadays known as Bayes' theorem - was presented in "An Essay towards solving a Problem in the Doctrine of Chances" which was read to the Royal Society in 1763 after Bayes' death. Bayes never published his work himself.
Ulrich W. Hütter (1910 – 1990)	Hütter was an Austrian-German engineer and professor. Hütter is an outstanding pioneer in the history of wind energy usage.

XIV. CURRICULUM VITAE

Christian Timo Geiss

23. Februar 1988	**Geboren in Karlsruhe** Eltern: Elke und Helmut Geiss Verheiratet mit: Oana Geiss
1994 - 1998	**Besuch der Grundschule in Karlsruhe-Rüppurr**
1998 - 2007	**Besuch des Max-Planck-Gymnasiums in Karlsruhe-Rüppurr**
21. Juni 2017	**Abitur**
2007 - 2010	**Studium des Wirtschaftsingenieurwesens an der Dualen Hochschule Baden-Württemberg, Karlsruhe (DHBW), Karlsruhe** Partnerunternehmen: Energie Baden-Württemberg AG (EnBW AG)
30. September 2010	**Abschluss zum Bachelor of Engineering (BEng)** Titel der Bachelorarbeit: Integration von EEG-Anlagen in Verteil- und Übertragungsstromnetze - Analyse und Simulation aus Sicht der Systemdienstleistungen
2010 - 2013	**Studium der Nachhaltigen Energieversorgungstechnologien an der Technischen Universität Chemnitz, Chemnitz**
22. April 2013	**Abschluss zum Master of Science (MSc)** Titel der Masterarbeit: Validierung von Ermüdungslasten einer 5 MW Offshore-Windturbine aus dem Testfeld „alpha ventus“
2013 - 2018	**Wissenschaftlicher Mitarbeiter am Lehrstuhl für Zerstörungsfreie Prüfung der Technischen Universität München, München**
2013 – 2017	**Wissenschaftlicher Mitarbeiter bei der Industrieanlagen-Betriebsgesellschaft GmbH (IABG mbH), Ottobrunn**
Seit 2017	**Geschäftsführer der GI-Engineering UG (haftungsbeschränkt), München**