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for Wind Installations with Novel Developments

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D.4.2 Optimised maintenance and logistic strategy models

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List of Abbreviations

Acronym	Description
A	Assets Consequences
ACTV	Advanced Crew Transfer Vessel
AEP	Annual Energy Production
BDFG	Brushless Doubly-Fed Generator
BPSO	Binary Particle Swarm Optimisation
BRB	Belief Rule-Based
CBM	Condition-Based Maintenance
CF	Capacity Factor
CfD	Contract for Difference
Ch.	Chapter
CO_2	Carbon dioxide
COE	Cost Of Energy
CPN	Cost Priority Number
CTV	Crew Transfer Vessel
D	Detectability (Non-Detection) of Failure
D4.2	Deliverable 4.2
DDE	Electric direct-drive train
DFIG	Doubly-Fed Induction Generator
DFP	Diagnosis and Fault Prognosis
DoW	Description of Work
E	Environment Consequences
EBA	Energy-based Availability
EESG	Electrically Excited Synchronous Generator
EPR	Energy Purchase Rate
F	Function Consequences
FER	Fuzzy Evidential Reasoning
FMEA	Failure Mode and Effect Analysis
FMECA	Failure Mode Effect & Criticality Analysis
FMMA	Failure Mode and Maintenance
FoF	Fix on Failure
FSV	Field Support Vessel
FTA	Fault Tree Analysis
GRA	Grey Relational Analysis
GRP	Grey Relational Projection
HV	High Voltage
IFHWED	Fuzzy Hybrid Weighted Euclidean Distance
IFN	Intuitionistic Fuzzy Numbers
IFOWD	Intuitionistic Fuzzy Ordered Weighted Distance
IFOWED	Intuitionistic Fuzzy Ordered Weighted Euclidean Distance
IFWED	Intuitionistic Fuzzy Weighted Euclidean Distance
LWK	Landwirtschaftskammer Schleswig-Holstein
MF	Moray Firth
MILP	Mixed Integer Linear Programming
MT TC	Total Cost of Material
MTBF	Mean Time Between Failure
MTTF	Mean Time To Failure
MTTR	Mean Time to Repair
NPC	Nominal Power Classification
NPV	Net Present Value
O	Operation Consequences, Occurrence of Failure

OEM	Original Equipment Manufacturer
OPEX	Operational Expenditure
PBC	Performance Based Contracting
PCB	Printed Circuit Board
PLS	Probability of Limit State
PM	Preventive Maintenance
POD	Probability Of Detection
RAMS	Reliability Availability Maintainability Safety & Security
RCM	Reliability Centred Maintenance
RDS-PP	Reference Designation System for Power Plants
ROC	Receiver Operating Characteristic
ROI	Return On Investment
RPN	Risk Priority Number
S	Severity of Failure
SA	Safety Consequences
SCADA	Supervisory Control And Data Acquisition
SCTV	Standard Crew Transfer Vessel
SOV	Service Operation Vessels
T4.2	Task 4.2 (the same applies for T4.3, T4.4, T4.5)
TBA	Time-Based Availability
TC AS	Total Cost of Access
TC LB	Total Cost of Labour
TVAC	Time-Varying Acceleration Coefficients
UPS	Uninterrupted Power System
WEI	Wind Energy Index
WG	West Gabbard
WMEP	Wissenshaftliches Mess und Evaluierungsprogramm
WP	Work Package
WRIG	Wound Rotor Induction Generator
WSD	Wasser und Schifffahrtsdirektion
WSDN	Wasser und Schifffahrtsdirektion Nord
WT	Wind Turbine

List of Symbols

Symbol	Description
A	Assets consequences
A_{el}	Energy based availability
A_i	Availability of wind turbine i
$A_{prod,j,t}$	Availability of wind turbine j at time step t.
A_{time}	Time based availability
A_{trans}	Time-based availability of main components that transport/transform electricity
C (& m)	Material specific parameters
CF	Cost of Failure and consequences
C_m	Criticality of failure modes
c_{tot}	Total costs of the system
$D(t)$	Damage
E	Environment consequences

E_{real}	Produced electricity considering downtime of the wind turbines and electrical infrastructure, wake losses and electrical losses
$E_{real,m}$	Sum of produced electricity in month *m*
E_{theor}	Theoretical possible electricity production with 100% availability, taking into account wind speeds and power curves but neglecting any losses
$E_{theor,j,t}$	Theoretical possible electricity production with 100% availability of wind turbine *j* at time step *t* based on wind speed at time step *t* and power curve of wind turbine *j*
$E_{theor,m}$	Sum of produced electricity in month *m*
F	Function consequences
$f(\Delta s)$	Long term distribution of stress ranges
$f_{\Delta\sigma}(s\|U)$	Probability density function for stress ranges
$f_{\Delta\sigma}(U)$	Long term probability density function for the mean wind speed
fp-rate	Ratio of false positives and total number of negatives
K_1, K_2	Material parameters
$Loss_{el}$	Losses of the produced electricity due to the electrical infrastructure
$Loss_{wake}$	Losses in electricity production due to wake effects in the wind farm
m	Downtime
$M(t)$	Exponential Maintainability
m_1, m_2	Material parameters
m_{Global}	Global Downtime
m_i	Downtime of sub-assembly *i*
n	Number of sub-assemblies, Number of WT
N	Number of cycles to failure
n_{tot}	Total number of negatives
O	Operation consequences
P	Probability of Occurrence
$P(t)$	Exponential Probability of Failure
P_{el}	Electricity price in month *m*
P_{el}	Electricity price in month *m*
PnD	Probability of not detection of failure
PO	Probability of occurrence of failure
p_{tot}	Total number of positive
S	Severity
s	Number of time steps in the simulation, one time step is one hour, therefore s = years × 365 × 24
Sa	Safety consequences
t	Mission phase duration, Time
$T_{downtime}$	Downtime of the wind turbine due to failures and services
$T_{lifetime}$	Lifetime of the wind turbine
t_o	Time that the turbines were available and ready to operate
tp-rate	Ratio of the true positives and the total number of positives
t_T	Total time in the period
U	Mena wind speed

V	Number of stress cycles per time unit
$Y(a)$	Geometry function
α	Failure mode ratio
$a(t)$	Crack length
a_{cr}	Critical values of crack length
β	Conditional probability
ΔK	Stress intensity factor
Δs	Stress range
Δs_C	Stress range corresponding to N_C
λ	Failure rate
λ_{Global}	Global failure rate
λ_i	Failure rate of sub-assembly *i*
λ_P	Basic failure rate

Executive Summary

This report describes the development of reliability, maintenance and logistics models and methodologies in LEANWIND Tasks 4.3 ("Reliability based design implications") and 4.2 ("Strategy optimisation").

The first step in optimising the O&M strategy of a wind turbine is the identification of its most critical components. The term "critical components" refers to the most vulnerable and crucial parts that are critical to the life-cycle and the maintenance plan of a wind turbine. The identification of critical components usually derives from the calculation of the risk of a potential failure, and therefore, the unavailability of the related sub-system or the entire wind turbine. In order to arrive at a list of critical components for a wind turbine of 8MW rated power, three types of methodologies were applied in Task 4.3. Firstly a literature survey was conducted, an analysis based on a RAMS approach was implemented and finally an experts' group judgement approach has been introduced, which is included in the appendix session, to be used whenever experts' opinions are available.

The databases examined in the literature survey refer to a mixed population of offshore and onshore wind turbines of varying rated power outputs. The time span of each database varies accordingly. Also some provide extra variables and components which can be introduced into the model as constraints or parameters that will affect the final categorization of critical components of a wind turbine. Based on the literature survey, a number of lists with critical components identification and criticality ratings are presented, which in part can be used as input to the O&M optimisation. On the whole, it is becoming quite clear that different methodologies lead to different ratings and categorisation of criticalities and components.

An extensive study and analysis based on the FMECA approach is presented, providing failure rates and downtime periods for existing wind farms, as well as a criticality ranking based on different sources. In addition, a raw trend analysis has been implemented in order to predict failure rates and downtimes for 5 MW and 8 MW wind turbines. Furthermore, a probabilistic analysis is performed, based on RAMS methodology, to estimate availability for large wind turbines. In addition, a distinction between wind turbine availability and wind farm system availability has been presented, to demonstrate the variations that may occur in the evaluation of the availability, according to the methodology used.

Degradation models are used in order to predict deterioration in certain components and sub-assemblies (mainly structural). Lastly, it is explained how degradation models will be integrated to the O&M strategy optimisation analyses via a risk based methodology.

In Task 4.2, the LEANWIND O&M strategy model has been developed. This is a strategic decision support tool designed for aiding stakeholders in selecting the optimal maintenance and logistics strategy for offshore wind farms. The development links to LEANWIND WP8 "Economic and Market Assessment", where this model will form the basis of the OPEX module of the LEANWIND full cost model and it will thus contribute in validating (by evaluating the costs and benefits) other innovations developed in the LEANWIND project.

The use of the O&M strategy model is demonstrated in three case studies with relevant decision problems for an offshore wind farm owner/operator: 1) Timing of jack-up vessel campaigns for heavy maintenance, 2) size and composition of crew transfer vessel (CTV) fleet, 3) timing of annual service campaigns.

These case studies are carried out for a LEANWIND reference wind farm consisting of 125 8 MW turbines with metocean conditions corresponding to West Gabbard. In the analyses, an optimal O&M and logistics solution is defined as the solution that minimises the sum of (direct) O&M costs and lost revenue due to downtime, i.e. maximising profit and having the optimal trade-off between costs and wind farm availability.

Focusing on case study (1) on jack-up vessel campaigns, results indicate that pre-chartering jack-up vessels for a set of campaign periods is a competitive strategy. Even if wind farm availability may become higher when chartering jack-up vessels as soon as the need arises ("fix-on-failure"), this may be offset by much higher charter costs than if having a smaller number of pre-determined campaigns. The competitiveness of such strategies over conventional fix-on-failure strategies is strengthened if the wind farm is large (e.g. 125 turbines or more) and if lower jack-up vessel day rates can be assumed for the charter strategy. Strategies with 3 campaign months spread evenly over the year were generally found to be advantageous, but exactly which months are optimal is likely to depend on the metocean conditions. As much as 4 campaign months could also be advantageous assuming high revenue per MWh produced and/or relatively high failure rates. For smaller farms (80 turbines) and lower rated power (5 MW) alternatives with two campaign periods, e.g. one month in spring and one month in the autumn, would be a better solution.

The results substantiate that optimising the jack-up charter strategy and optimising the CTV fleet composition both offer substantial economic potential for the wind farm owner/operator. There was also a smaller but still significant potential for increasing profitability by starting annual service campaigns in late spring rather than earlier. We identified a risk of selecting sub-optimal strategies if not viewing different decision problems as a whole: Less robust vessel fleets might not have the capacity to complete all annual services in time, and with a more robust vessel fleet one can concentrate the annual service campaign in the summer months where the expected downtime losses are lowest.

The problem of jack-up vessel charter optimisation is associated with much larger variability in results since failures requiring heavy maintenance and jack-up vessels are much rarer but have much higher impact than failures requiring only CTVs. Therefore, there is less certainty for a wind farm operator that the jack-up vessel campaign strategy with the best expected (average) profitability actually turns out to be the most profitable solution for that particular wind farm over the particular years it is operational.