Remaining lifetime prediction modelling

A case-study

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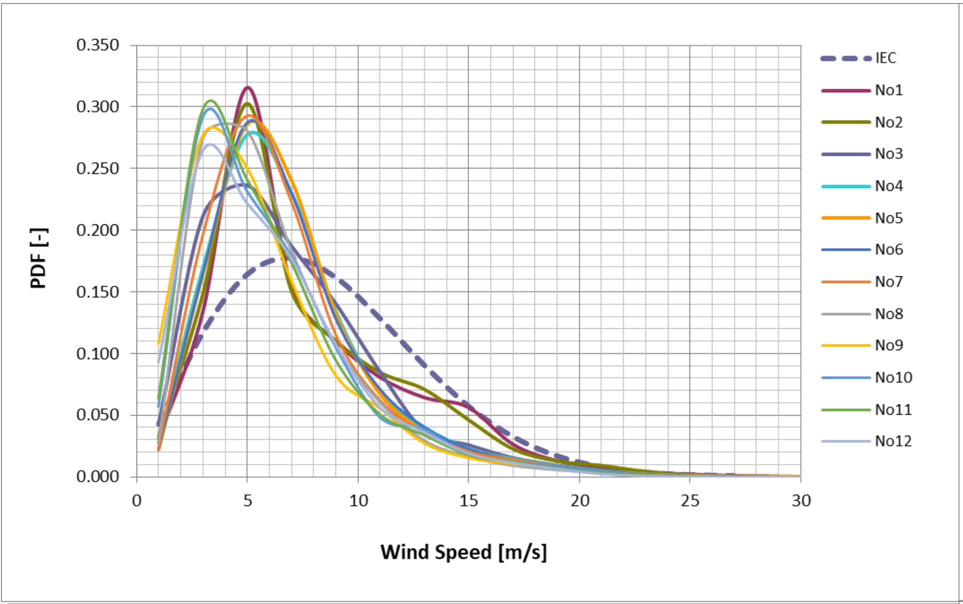
Project Steps

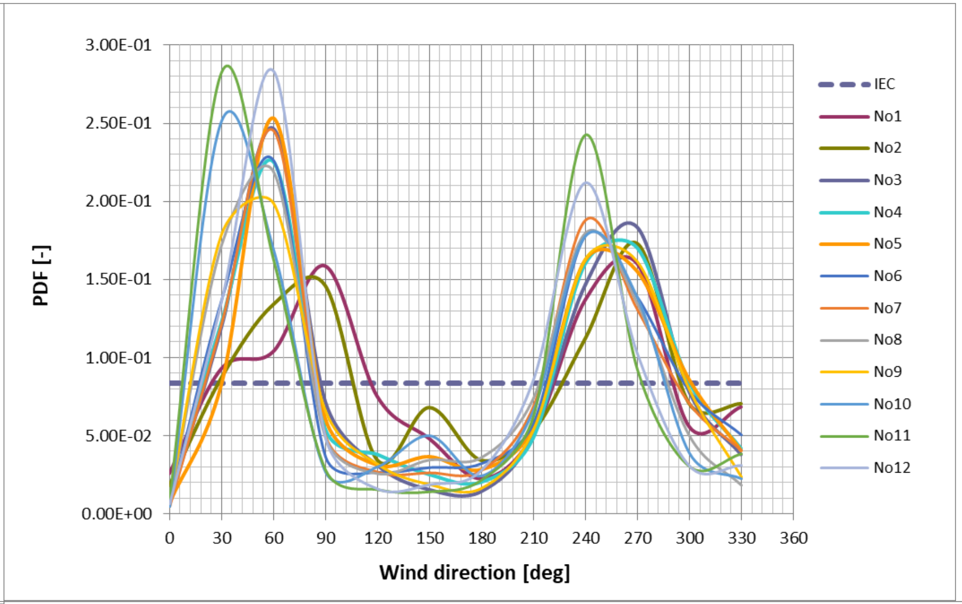
- STEP 1 : CFD micrositing study, turbines inflow conditions
- STEP 2 : Building turbine's generic aeroelastic model, define load sensors along the turbine's subsystems
- STEP 3 : Create loads (DELs) database addressing IEC-61400-1.Ed3 fatigue limit state DLCs with IEC and (a subset of) site external conditions
- STEP 4 : Interpolate the full set of site external conditions in the loads database (Neural Networks are used)
- STEP 5 : Fatigue damage calculations per turbine and sensor, estimation of expected lifetime through comparisons against IEC damage calculations
- STEP 6 : Suggest a sector management scheme for fatigue loads reduction (not presented here)

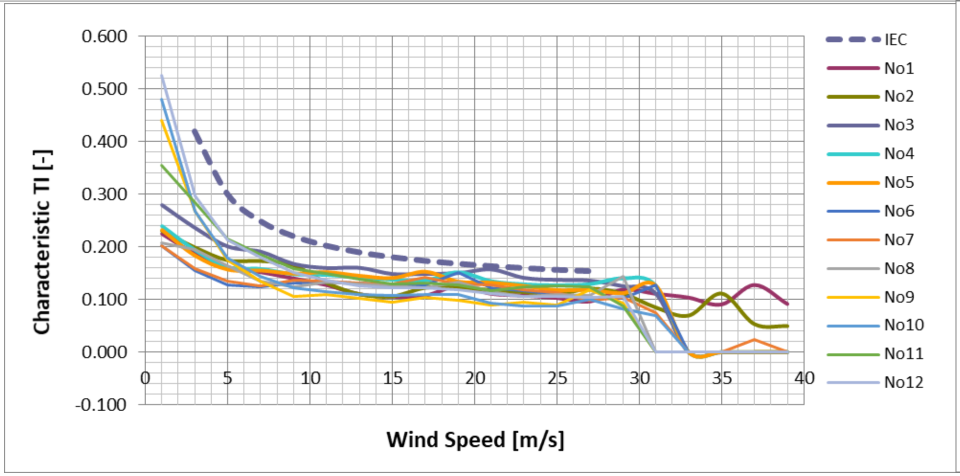
STEP1 : Micrositing

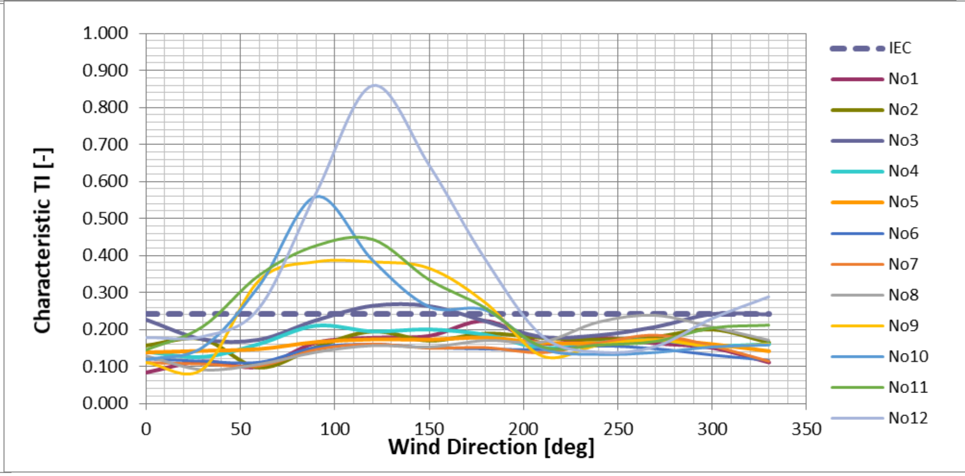
- Micrositing analysis provides inflow data seen by each turbine of the wind farm
- The results needed derive from the inhouse codes *iWind-Flow.V2017* (CFD flow analysis) and *iWind-Farm.V2017* (wind farm analysis)
- Parameters used as turbine inflow conditions per wind speed and direction bin are:
    - *Air density*
    - *Characteristic turbulence intensity (P90 plus complex terrain correction)*
    - *Flow inclination*
    - *Wind shear exponent*
    - *Wind veer*

STEP1 : Micrositing









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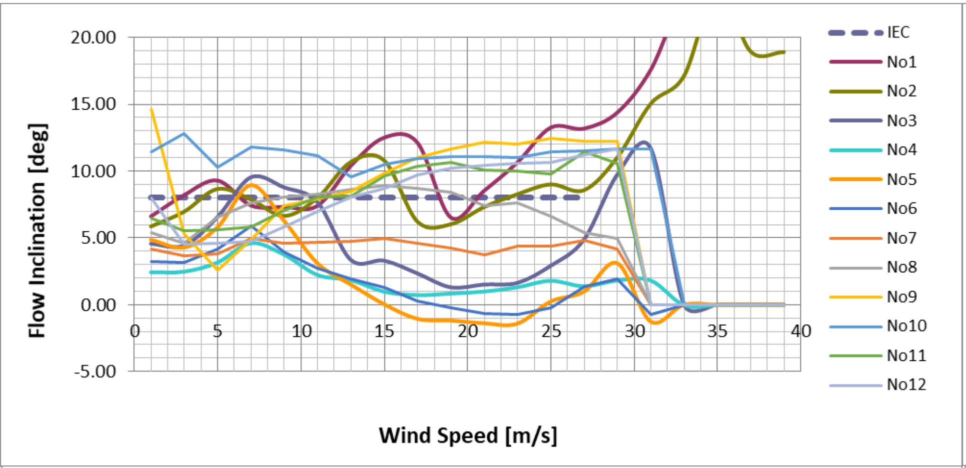
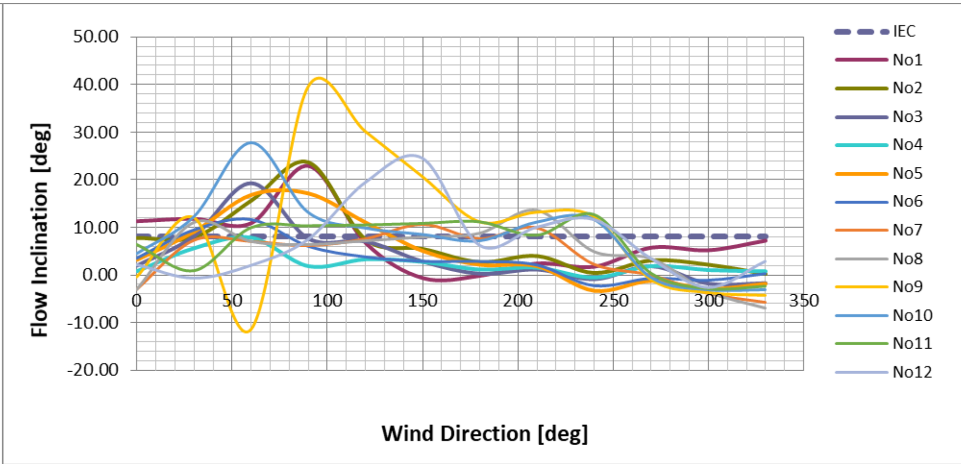
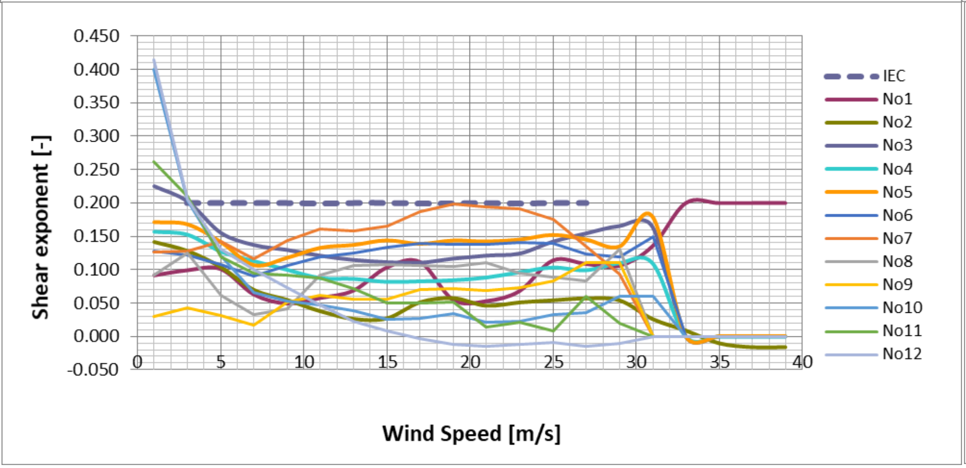
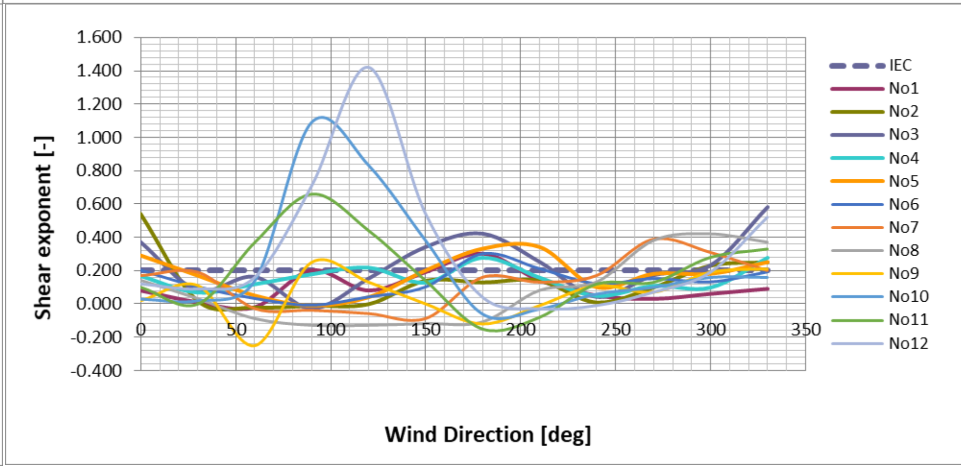
STEP1 : Micrositing







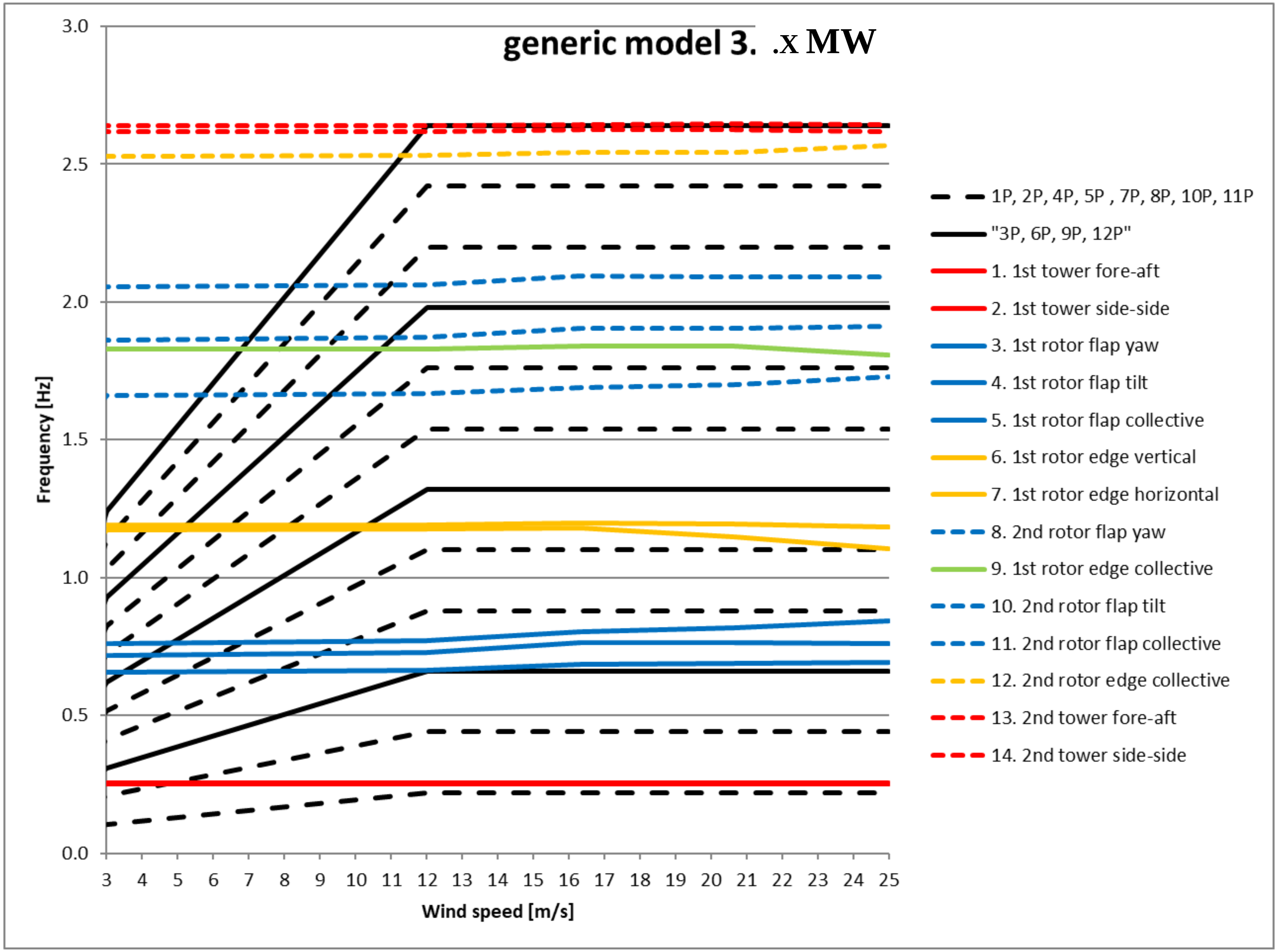


WT	DIR [deg	WSP [m/	PDF	ChTI	INC [deg]	SHE [exp]	VEE [deg/
1	0	3.0	7.698E-03	0.0874	11.32	0.080	0.0496
1	30	3.0	9.828E-03	0.1449	11.81	0.010	0.0453
1	60	3.0	8.605E-03	0.1691	10.93	-0.020	0.0282
1	90	3.0	1.803E-02	0.2289	22.94	0.200	0.0187
1	120	3.0	1.487E-02	0.2714	6.74	0.080	-0.0003
1	150	3.0	8.523E-03	0.2990	-0.65	0.190	-0.0977
1	180	3.0	6.629E-03	0.3025	-0.15	0.300	-0.0296
1	210	3.0	8.883E-03	0.2726	2.44	0.140	0.0083
1	240	3.0	1.036E-02	0.2634	1.75	0.050	0.0014
1	270	3.0	1.240E-02	0.2450	5.76	0.030	-0.0519
1	300	3.0	9.912E-03	0.2036	5.21	0.060	-0.0779
1	330	3.0	1.879E-02	0.1369	7.23	0.090	-0.0126
1	0	5.0	9.624E-03	0.0920	11.32	0.080	0.0496
1	30	5.0	2.357E-02	0.1265	11.81	0.010	0.0453
1	60	5.0	1.439E-02	0.1369	10.93	-0.020	0.0282
1	90	5.0	6.239E-02	0.2461	22.94	0.200	0.0187
1	120	5.0	4.207E-02	0.1921	6.74	0.080	-0.0003
1	150	5.0	2.906E-02	0.1806	-0.65	0.190	-0.0977

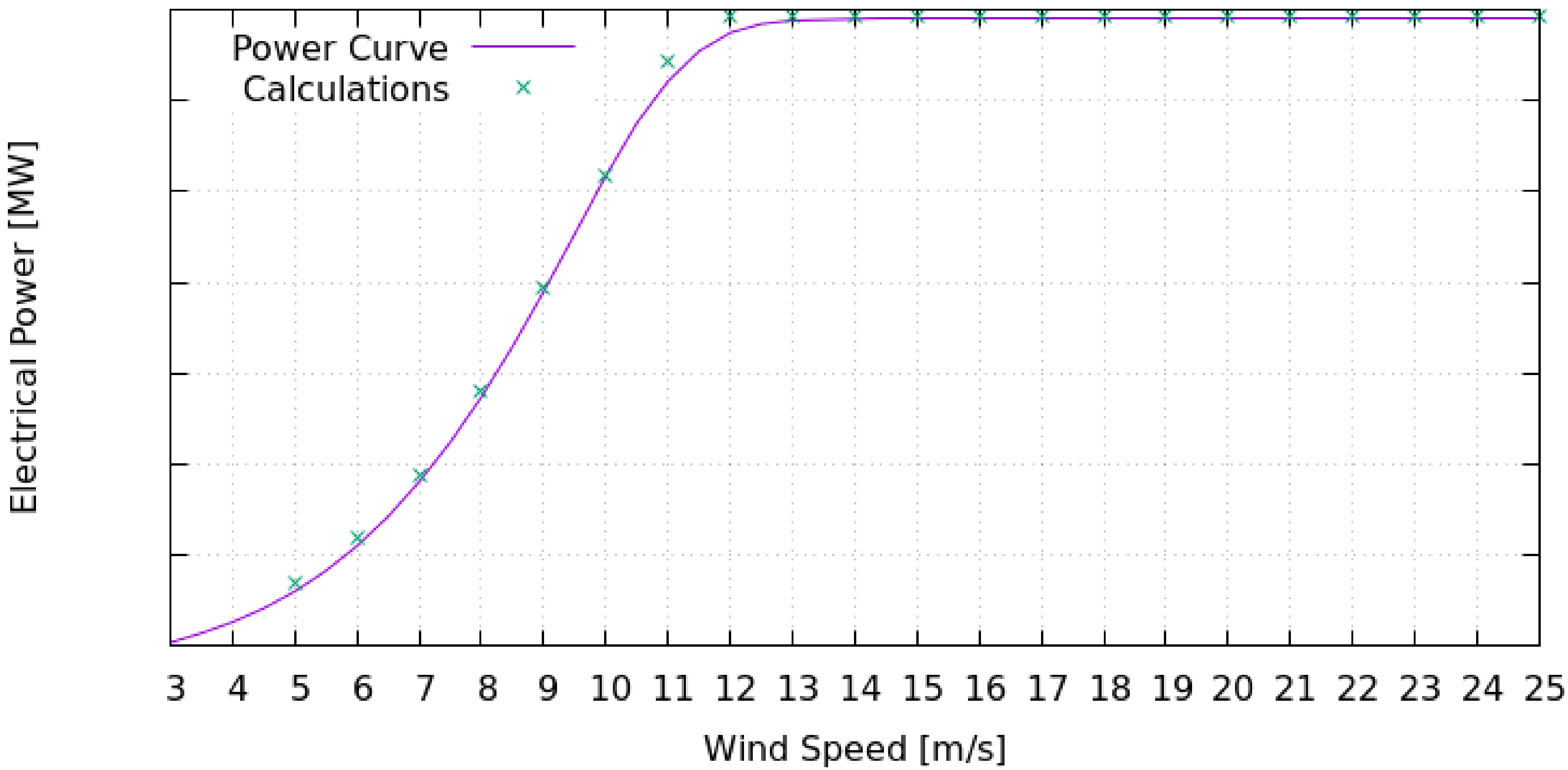
STEP2 : Generic Turbine Aeroelastic Model

- Turbine Aeroelastic Model for *iGAST.V2018*
- Generic model constructed based on:
  - *Information from turbine brochures, including general specifications, components' masses, power curves, etc.*
  - *Up/Down scaling other available turbine designs*
  - *Detailed drawings when available*
  - *SCADA data for pitch and variable speed schedules, controller tuning etc.*
- Extended use of SCADA data for Turbine Model validation when 10min loads statistics are also recorded (modern turbines)

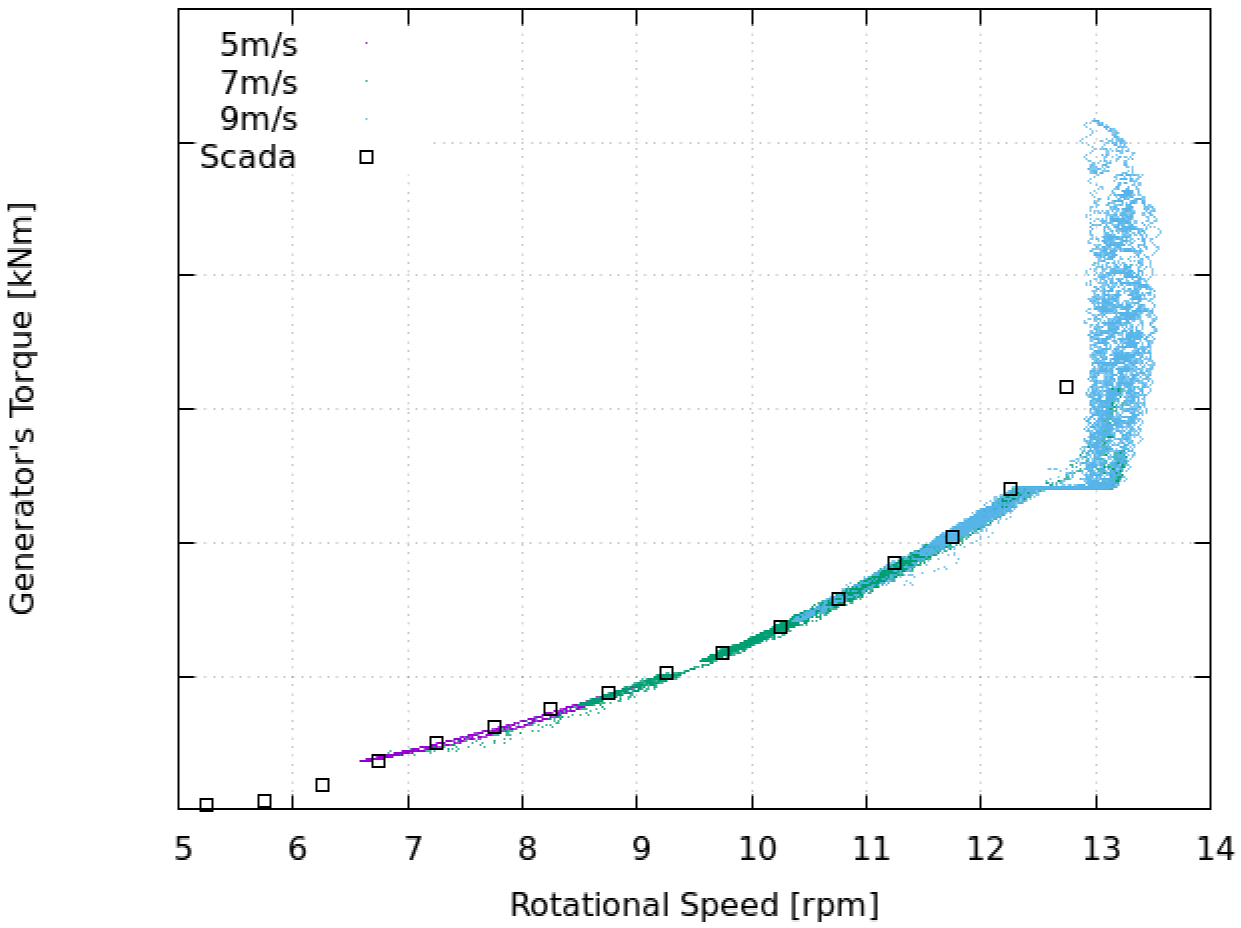
STEP2 : Generic Turbine Aeroelastic Model



Campbell diagram


Power Curve
Calculations
Electrical Power [MW]
3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25
Wind Speed [m/s]

STEP2 : Generic Turbine Aeroelastic Model



Variable speed part (T-ω) vs Scada

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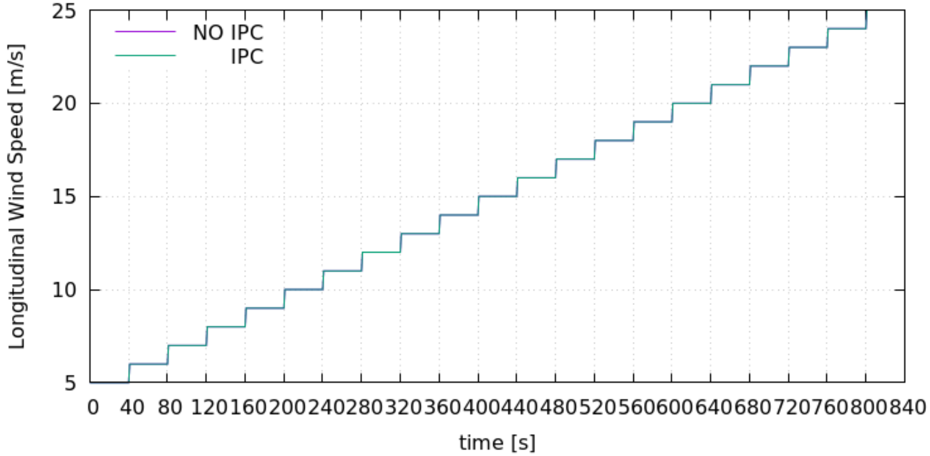
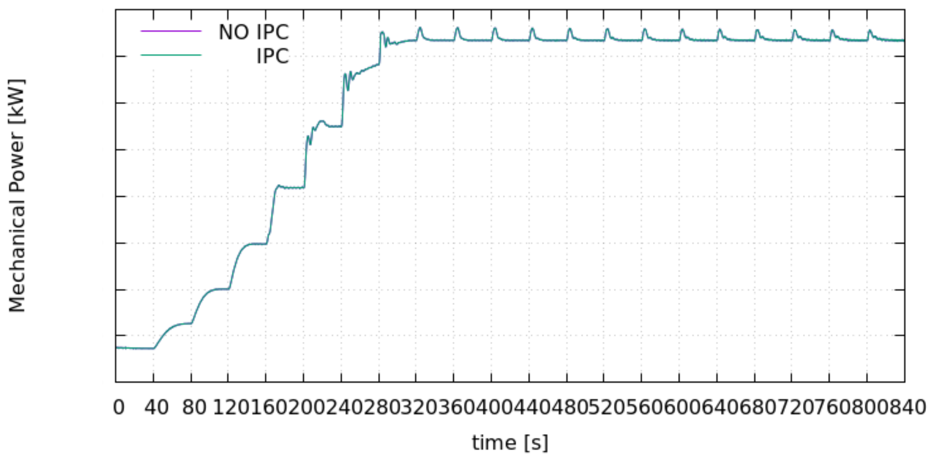
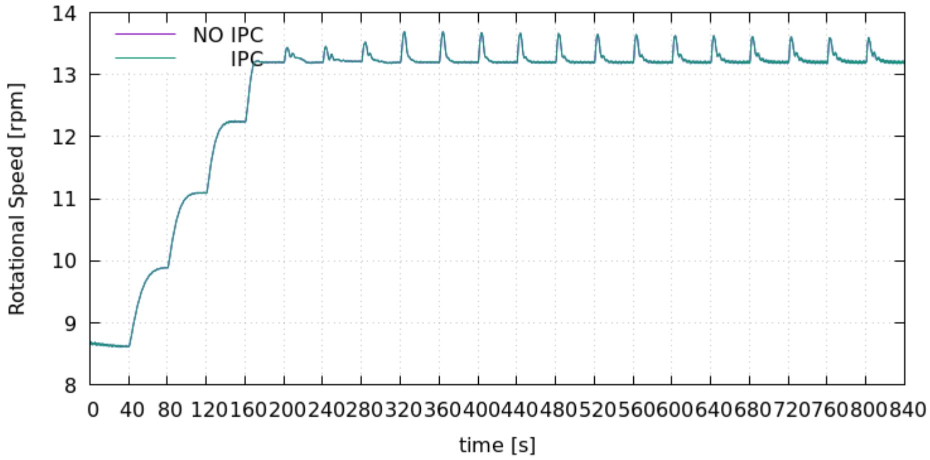
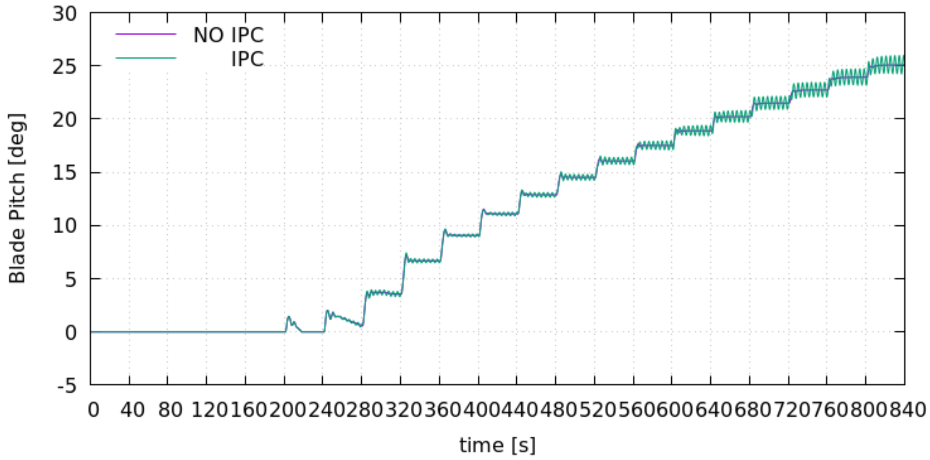
STEP2 : Generic Turbine Aeroelastic Model



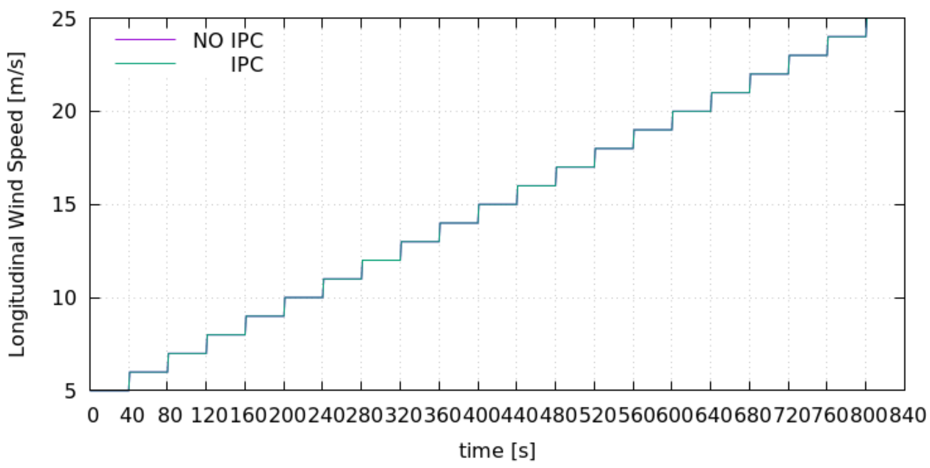


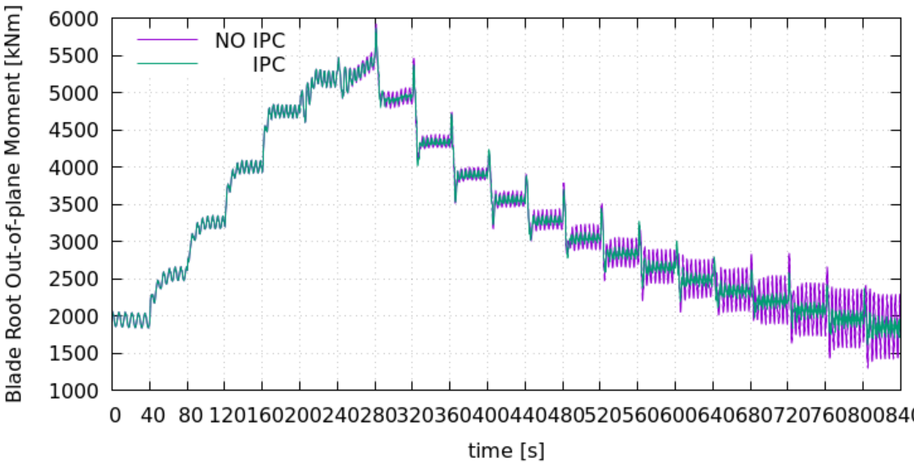


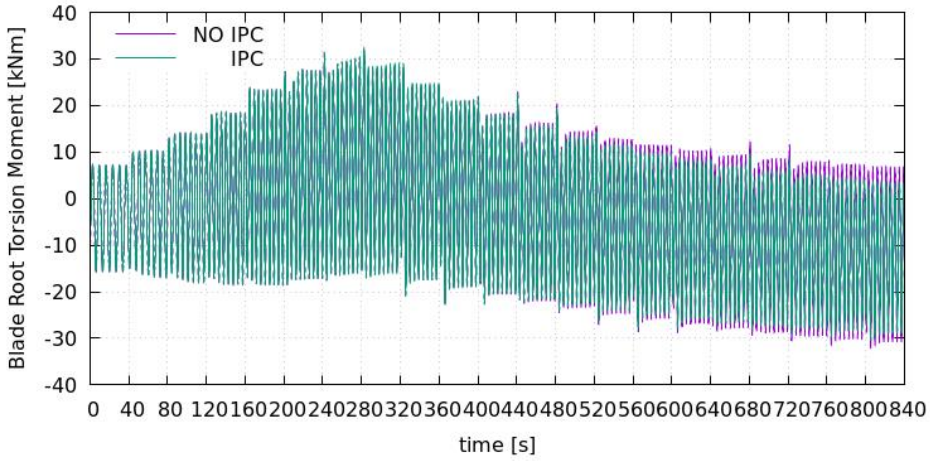


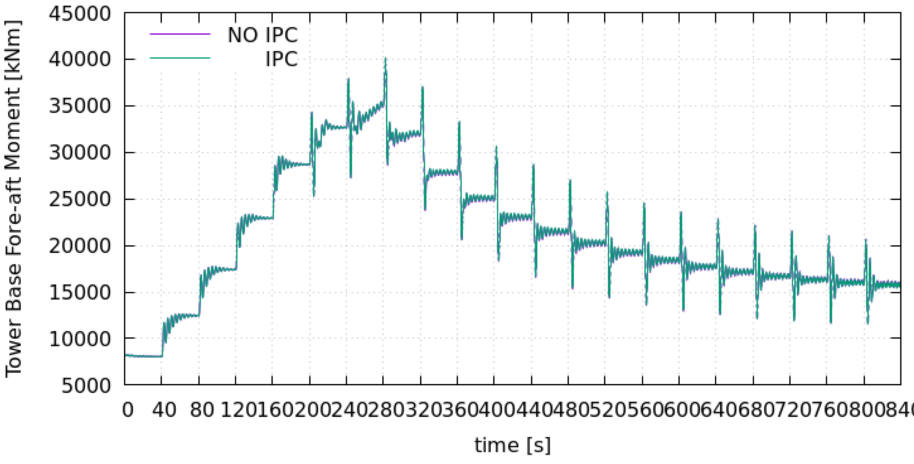
Step-up demonstrating IPC activity

STEP2 : Generic Turbine Aeroelastic Model









Step-up demonstrating IPC activity

STEP2 : Validation of the Generic Model

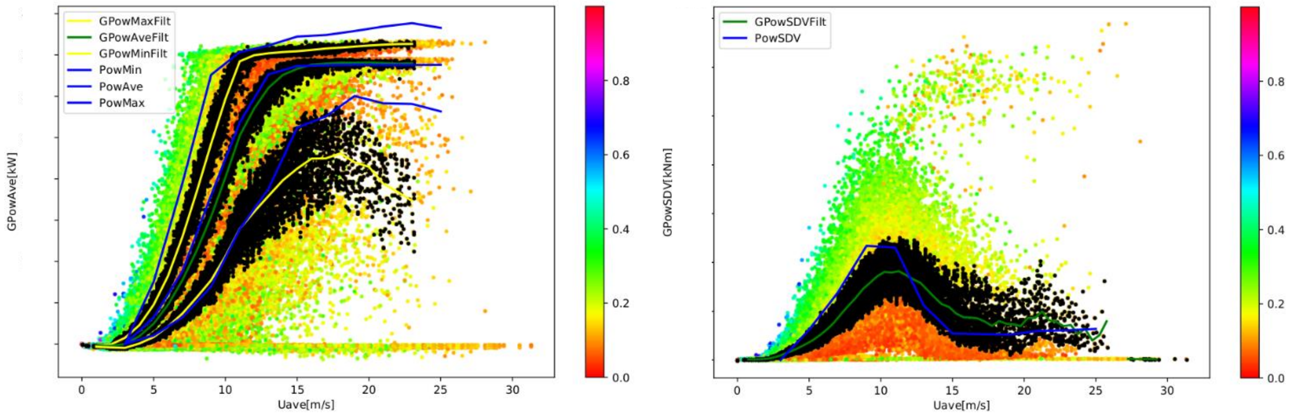


Figure 1 *Comparison between SCADA records and aeroelastic simulations for IEC DLC1.2. Minimum, average and maximum electrical power output on the left, sdv on the right.*

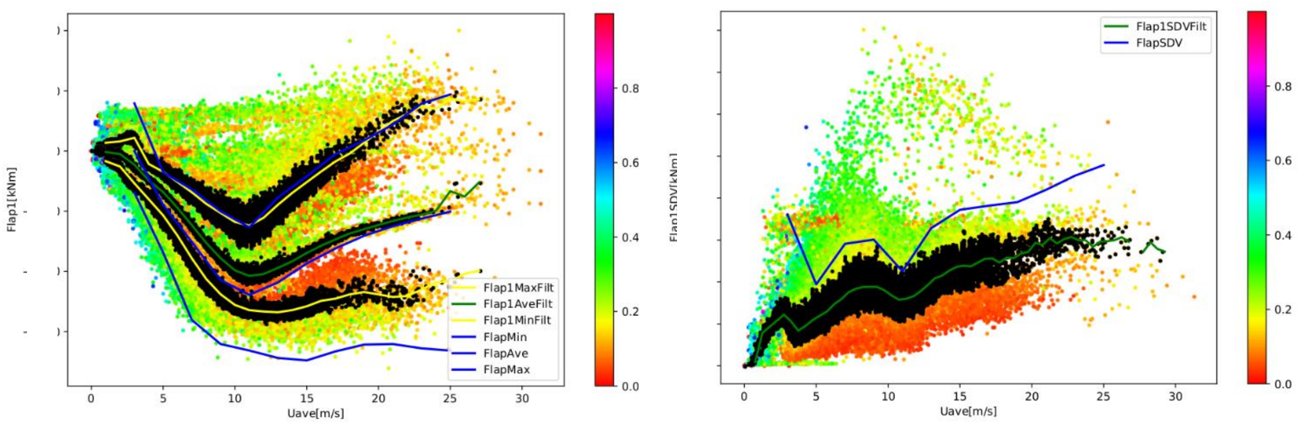


Figure 2 *Comparison between SCADA records and aeroelastic simulations for IEC DLC1.2. Minimum, average and maximum flapwise moment at blade root on the left, sdv on the right.*

STEP2 : Validation of the Generic Model

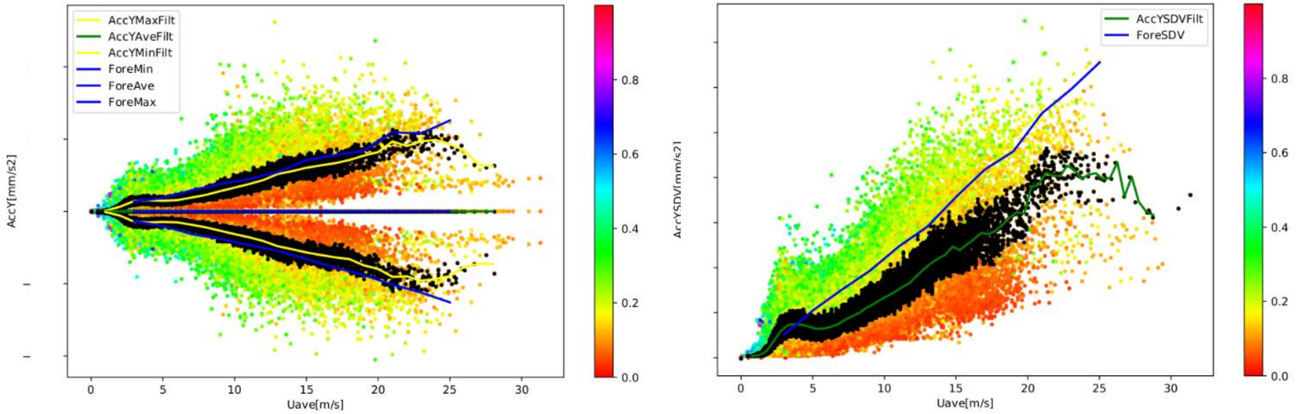


Figure 1 *Comparison between SCADA records and aeroelastic simulations for IEC DLC1.2. Minimum, average and maximum fore-aft acceleration at tower top on the left, sdv on the right.*

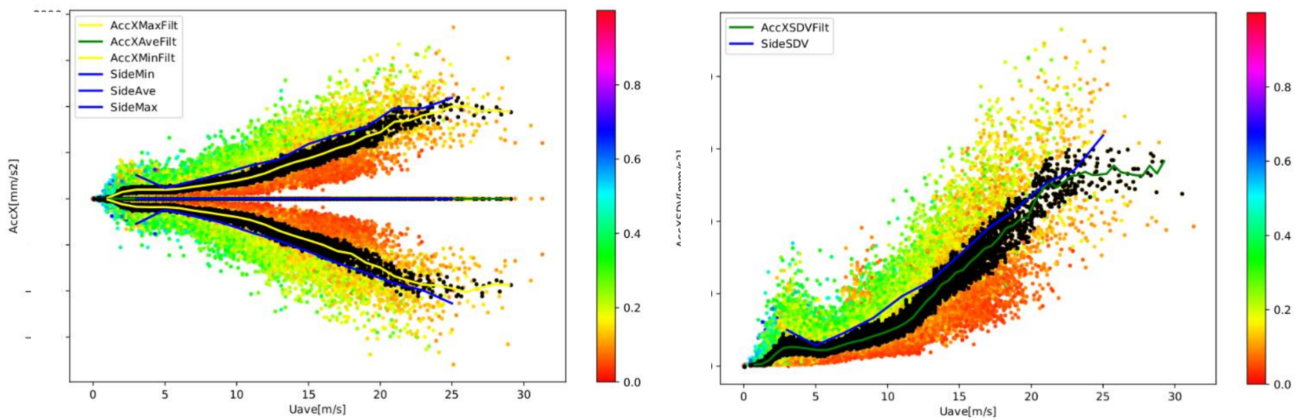


Figure 2 *Comparison between SCADA records and aeroelastic simulations for IEC DLC1.2. Minimum, average and maximum side-side acceleration at tower top on the left, sdv on the right.*

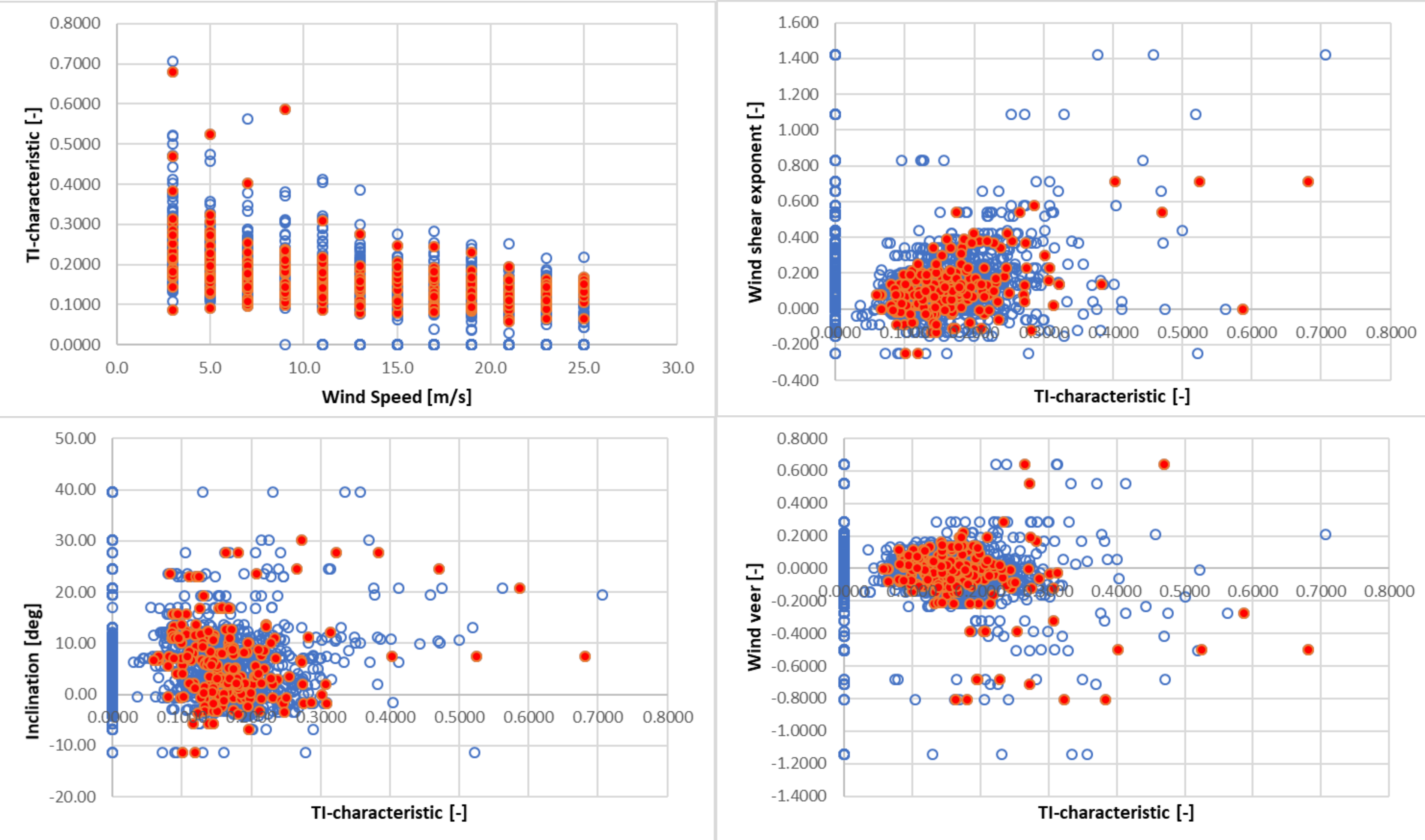
STEP3 : DELs database

- Fatigue limit state calculations for relevant IEC DLCs
- Fatigue limit state calculations for site conditions
- For each 10 min aeroelastic run (IEC and site)
  - *Use two coordinate systems per turbine subsystem (in 45^o offset) and two reference systems (fixed and rotating, when relevant)*
  - *Deploy sensors along blades, tower and drivetrain*
  - *Calculate Markov Matrix for 6 loads per sensor and ref. system*
  - *For Wöhler's exponents m = 4,6,8,10,12,14 calculate equivalent loads (DELs) with and without Goodman correction*

	DLC	Wind condition	V_{hub} (m/s)	#of V_{hub}	Conditions	Comments	Seeds	#Runs
1. Power production	1.2	NTM	3, 5, …, 23, 25	12	Yaw = 0, ±8	2 seeds/yaw	6	72
2. Power prod./fault	2.4	NTM	5, 7, 11, 17, 23	5	Yaw = ±30	3 seeds/yaw	6	30
3. Start up	3.1	NWP	3, 12, 22	3	Yaw = 0, ±8	-	-	9
4. Normal shutdown	4.1	NWP	3, 12, 25	3	Yaw = 0, ±8	-	-	9
6. Parked (idling)	6.4	NTM	1, 27	2	Yaw = 0, ±8	2 seeds/yaw	6	12
								132

Run matrix of IEC Class IIA fatigue load cases

STEP3 : DELs database



Selecting a subset of site conditions (blue: full set, red: subset)

STEP3 : DELs database

DATABASE :

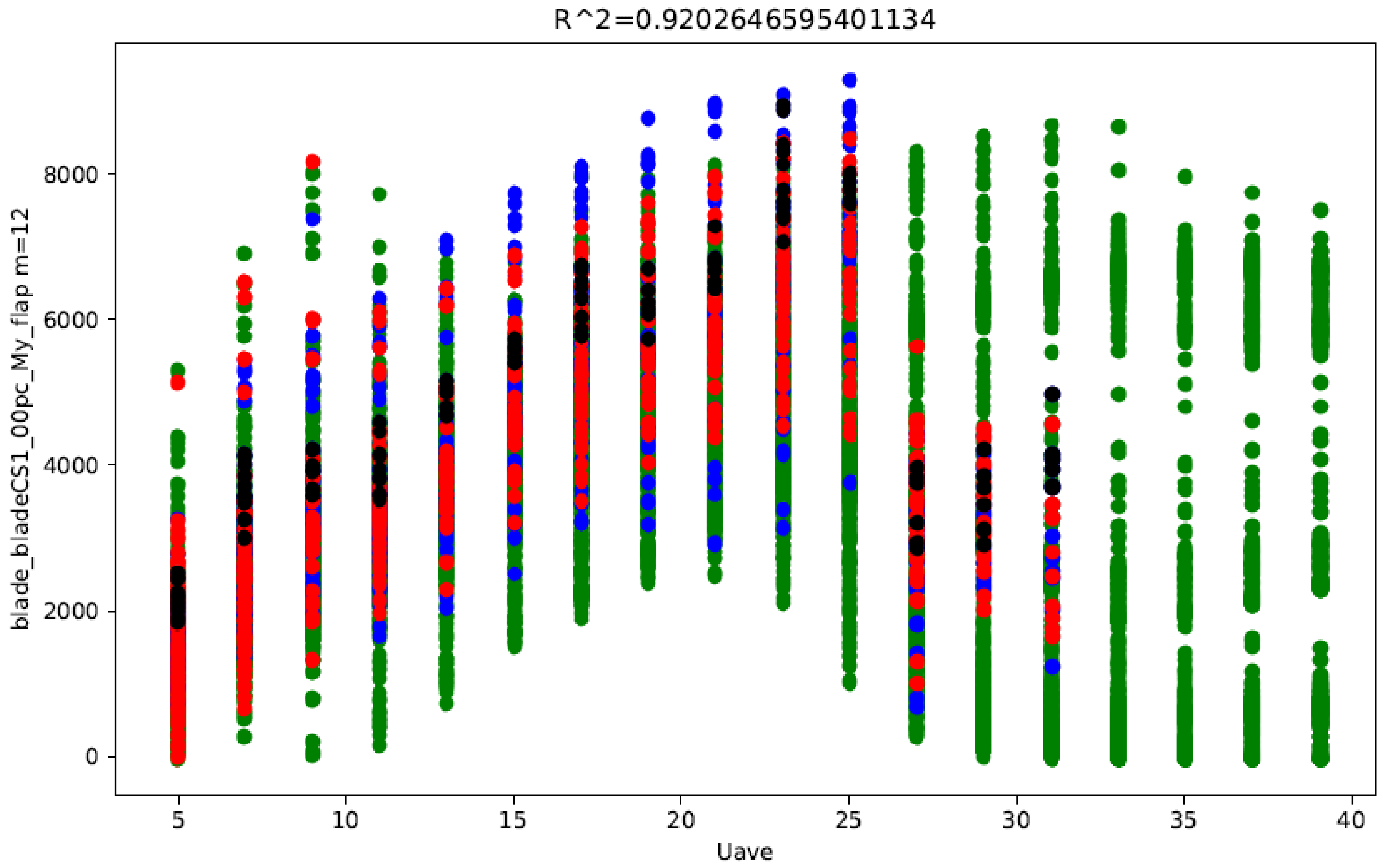
iec_db_rfc.csv	*132 aeroelastic runs*	*612 loads@sensors*	*w/o Goodman*
iec_db_good.csv	*132 aeroelastic runs*	*612 loads@sensors*	*w Goodman*
all_db_rfc.csv	*1500 aeroelastic runs*	*612 loads@sensors*	*w/o Goodman*
all_db_good.csv	*1500 aeroelastic runs*	*612 loads@sensors*	*w Goodman*

Uave	Seed	Density	Yaw	TI	Inclinat	Shear	Veer	blade_bladeCS1_00pc_Fy_edge m=04	... 612 times
5.00E+00	4	1.23E+00	-3.00E+01	2.99E-01	8.00E+00	2.00E-01	0.00E+00	4.18E+02	
5.00E+00	5	1.23E+00	-3.00E+01	2.99E-01	8.00E+00	2.00E-01	0.00E+00	4.25E+02	
5.00E+00	6	1.23E+00	-3.00E+01	2.99E-01	8.00E+00	2.00E-01	0.00E+00	4.22E+02	
7.00E+00	4	1.23E+00	-3.00E+01	2.48E-01	8.00E+00	2.00E-01	0.00E+00	4.56E+02	
7.00E+00	5	1.23E+00	-3.00E+01	2.48E-01	8.00E+00	2.00E-01	0.00E+00	4.57E+02	
7.00E+00	6	1.23E+00	-3.00E+01	2.48E-01	8.00E+00	2.00E-01	0.00E+00	4.57E+02	
1.10E+01	4	1.23E+00	-3.00E+01	2.01E-01	8.00E+00	2.00E-01	0.00E+00	4.93E+02	
1.10E+01	5	1.23E+00	-3.00E+01	2.01E-01	8.00E+00	2.00E-01	0.00E+00	4.99E+02	
1.10E+01	6	1.23E+00	-3.00E+01	2.01E-01	8.00E+00	2.00E-01	0.00E+00	4.86E+02	
1.70E+01	4	1.23E+00	-3.00E+01	1.73E-01	8.00E+00	2.00E-01	0.00E+00	5.13E+02	
1.70E+01	5	1.23E+00	-3.00E+01	1.73E-01	8.00E+00	2.00E-01	0.00E+00	5.13E+02	
1.70E+01	6	1.23E+00	-3.00E+01	1.73E-01	8.00E+00	2.00E-01	0.00E+00	5.09E+02	

STEP4 : Neural Network (NN) Regression

- The full set of STEP1 external conditions is regressed in the DELs database
- Regression is performed using a single-inner layer neural network
- Regression is performed for each of the (612) load signals individually
- To minimize the randomization impact introduced by the neural network to the regressed loads we average six NNs results per signal
- NN regression R^2 is of the order 90%+ for all signals

STEP4 : Neural Network (NN) Regression



Blue: data subset, Red: subset regressed, Green: full set regressed, Black: IEC

STEP5 : Lifetime estimation at site

- Fatigue damage at site per turbine and sensor/signal is compared against its design value (IEC results)
- From the comparison one can evaluate the (minimum) lifetime of the sensor's subsystem for the particular signal

$$D_{y,\mathrm{IEC}} = n_{\mathrm{eq,1year}} \frac{y_{\mathrm{IEC}}}{R_{u^m}} \sum_{j=1}^{J} p_{j,\mathrm{IEC}} R^m_{\mathrm{eq},j,\mathrm{IEC}}$$

$$y_{\mathrm{IEC}} \sum_{j=1}^{J} p_{j,\mathrm{IEC}} R^m_{\mathrm{eq},j,\mathrm{IEC}} = y_{\mathrm{OLD}} \sum_{j=1}^{J} p_{j,\mathrm{OLD}} R^m_{\mathrm{eq},j,\mathrm{OLD}} + y_{\mathrm{NEW}} \sum_{j=1}^{J} p_{j,\mathrm{NEW}} R^m_{\mathrm{eq},j,\mathrm{NEW}}$$

STEP5 : Lifetime estimation at site

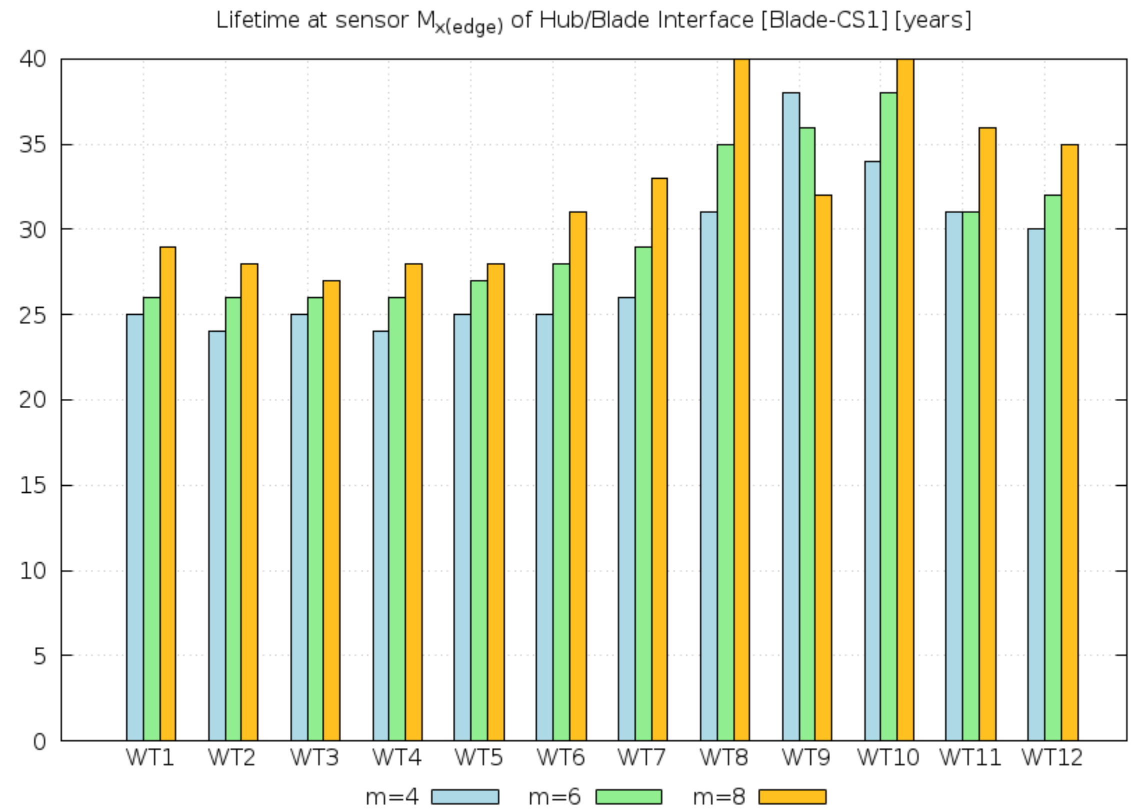


Figure 1 Lifetime at sensor Mx (edge) of the Hub/Blade interface on Blade-CS1 (for exponents m=4, 6, 8 – without Goodman correction).

Minimum lifetime for all turbines

STEP5 : Lifetime estimation at site

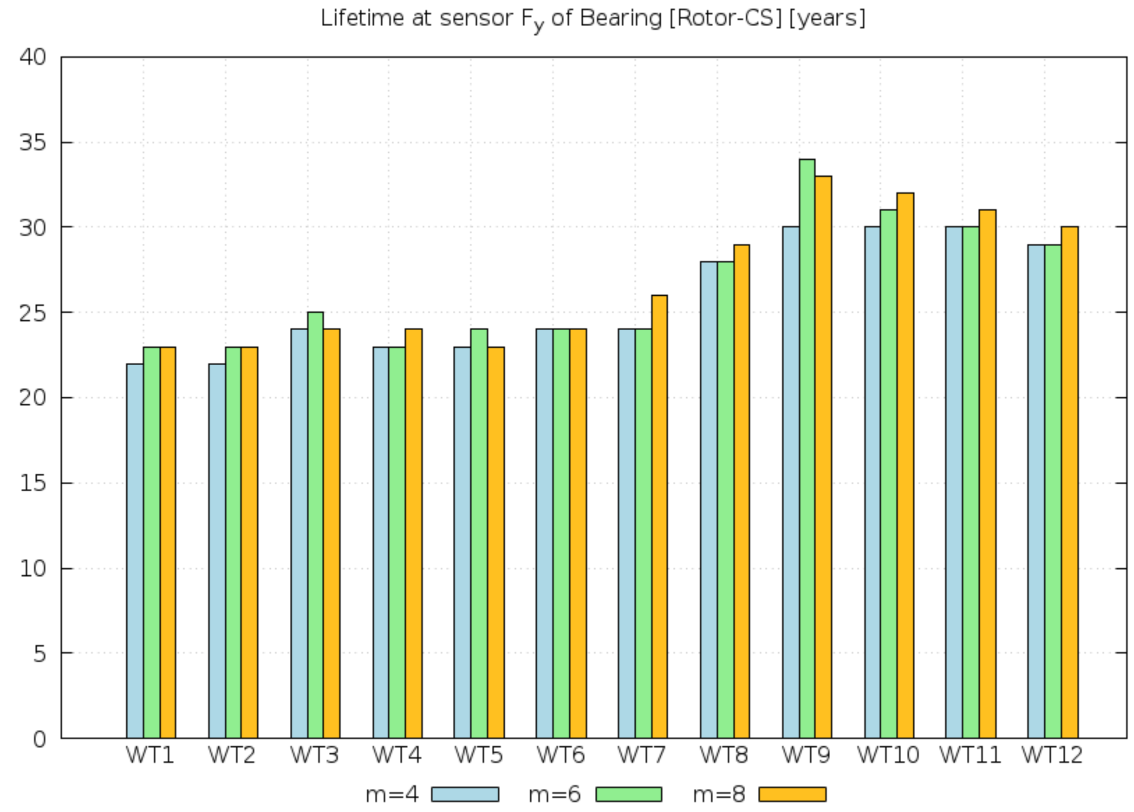


Figure 1 Lifetime at sensor Fy of the Bearing on Rotor-CS (for exponents m=4, 6, 8 – without Goodman correction).

Minimum lifetime for all turbines

STEP5 : Lifetime estimation at site

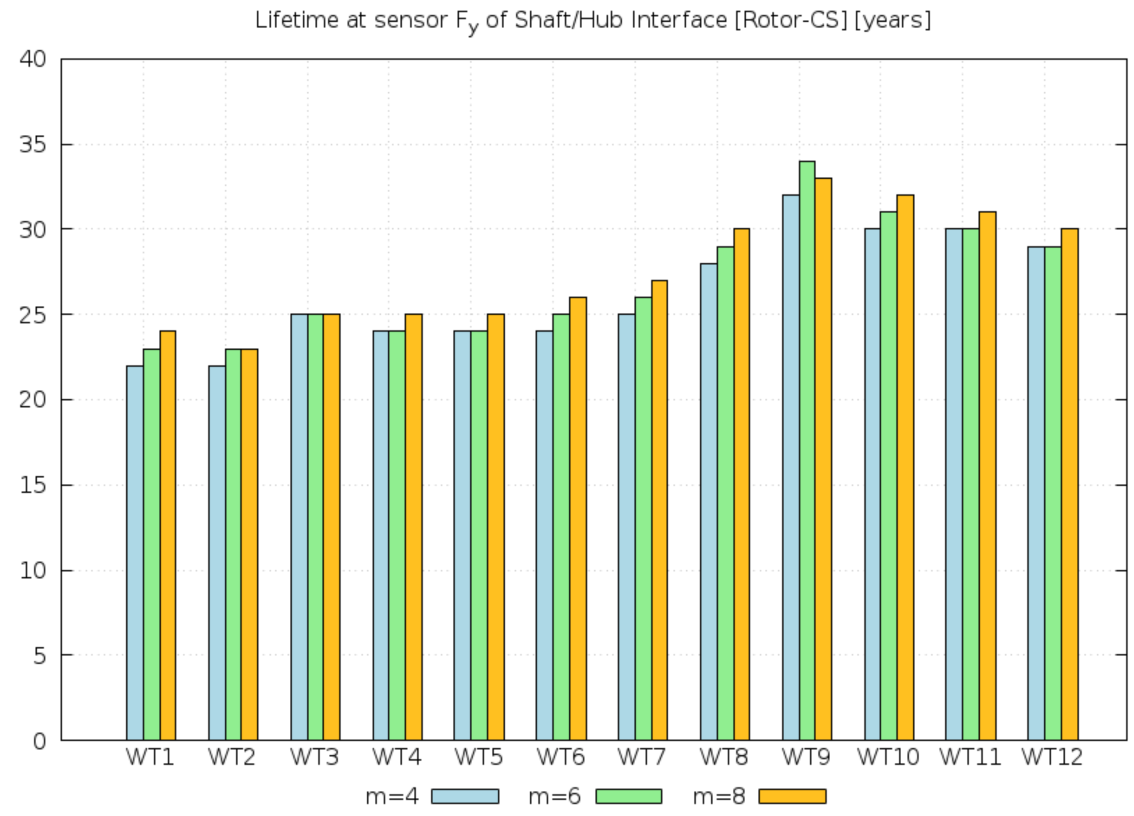


Figure 1 Lifetime at sensor Fy of the Shaft/Hub interface on Rotor-CS (for exponents m=4, 6, 8 – without Goodman correction).

Minimum lifetime for all turbines

STEP5 : Lifetime estimation at site

Table 1 Total rotor revolutions for 20 years of operation for IEC IIa and the twelve wind turbines, based on the wind speed probability.

	20y total revs.	% of IEC	Total years
IEC IIa	1.028E+08	-	20.0
WT1	9.512E+07	92.5%	21.6
WT2	9.355E+07	91.0%	22.0
WT3	8.582E+07	83.5%	24.0
WT4	9.083E+07	88.3%	22.6
WT5	9.137E+07	88.8%	22.5
WT6	9.174E+07	89.2%	22.4
WT7	8.736E+07	85.0%	23.5
WT8	7.759E+07	75.5%	26.5
WT9	6.821E+07	66.3%	30.2
WT10	7.354E+07	71.5%	28.0
WT11	7.158E+07	69.6%	28.7
WT12	7.285E+07	70.8%	28.2

STEP5 : Lifetime validation against SCADA

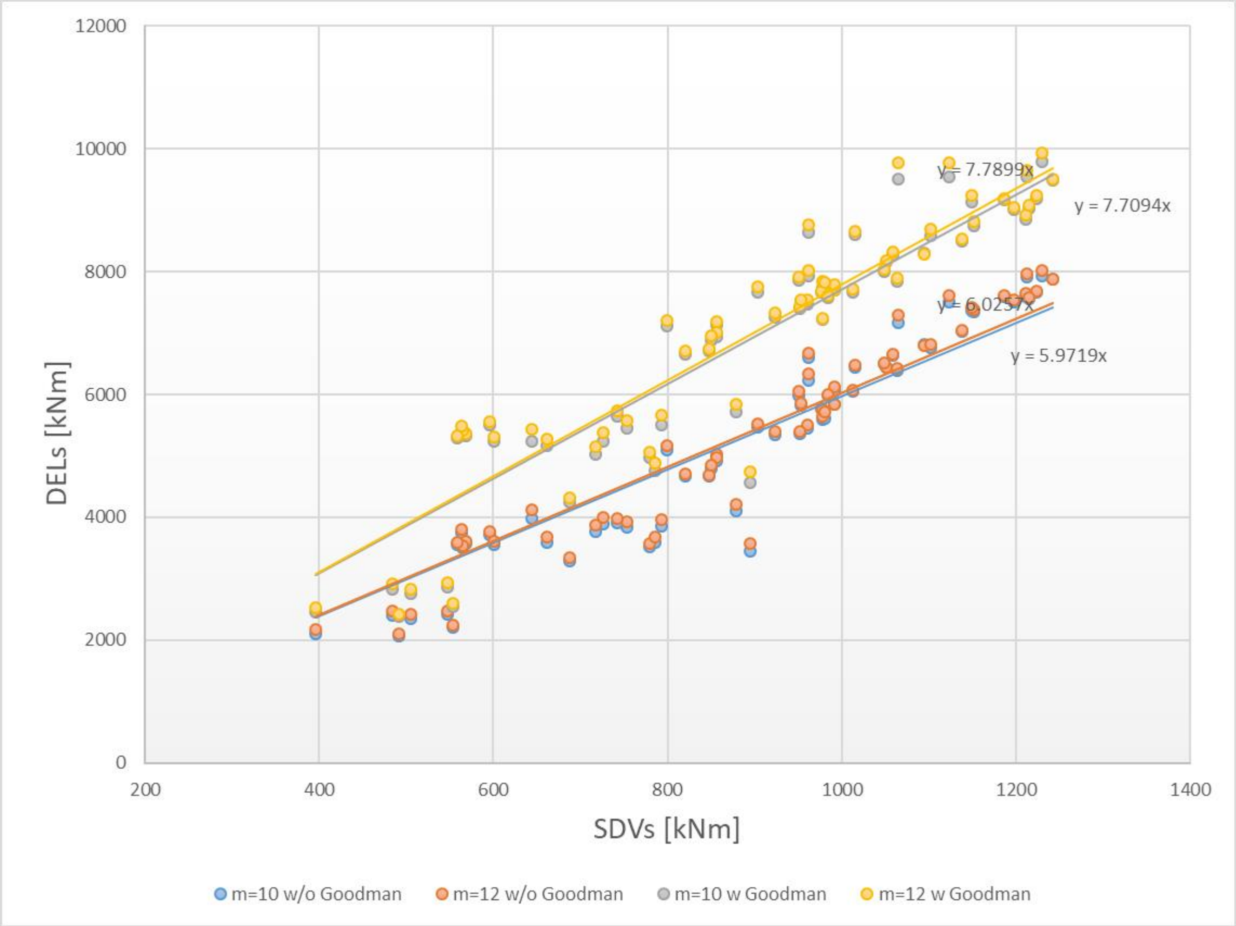


Figure 1 SDVs to DELs proportionality coefficients. Each coloured dot on the plot corresponds to a 10min aeroelastic calculation for IEC DLC1.2. Results are presented for root flap bending moment, for m=10 and m=12, with and without Goodman correction on DELs.

STEP5 : Lifetime validation against SCADA

Table 1 Damage Ratios and expected lifetimes calculated for flap bending moment at blade root. Damage ratios (single year) of SCADA vs IEC and SITE calculations are provided for m=10 and 12 with (w) and without (w/o) Goodman correction.

CASE	m=10 w/o Goodman	m=12 w/o Goodman	m=10 w Goodman	m=12 w Goodman
Damage_SCADA/IEC calc	0.06	0.08	0.05	0.07
Damage_SCADA/SITE calc	0.25	0.45	0.31	0.66
Years_IEC	20	20	20	20
Years_SCADA	340	236	427	286
Years_SITE	85	106	134	189
m	10	12	10	12
DELs/SDV proportionality	5.97	6.02	7.71	7.79

CONCLUSIONS

The lifetime extension results obtained can be classified into two categories:

Category 1: It addresses turbine subcomponents whose fatigue damage is mainly due to aerodynamic loads which are directly linked to the site conditions (air density, turbulence intensity, shear, veer and inclination, etc). In this category belong the main turbine substructures, blades, nacelle frame, tower and their joints (bolted or welded) as well as main subsystems such as the pitching and yawing mechanisms.

In a worst-case scenario, failure in this Category could result in damage to nearby buildings or people. They also signify substantial economic loss.

Category 2: It addresses machinery components whose fatigue damage is mainly due to gravity and inertia loads and, thus, they are insensitive to the site conditions other than the wind speed distribution. What matters in this case is the total number of weight cycles occurring in a certain period of time, which is related to the wind speed statistics through the variable speed operation (fewer cycles at lower mean annual wind speeds). A typical representative of this category is the main bearing(s) of the drivetrain.

Failure in this Category can be easily prevented through inspection, repair and renovations of the bearing seats, etc. The possible economic loss is low or moderate.

The results obtained suggest:

- Category 1: The total fatigue lifetime of substructures and subsystems in this category for all wind turbines is *at least* 39 years. This figure is the minimum obtained from all sensors and loads in this category and addresses the edgewise moment (M_x) at 1/3 of the blade span. All other blade, tower and drivetrain (non-rotating system) sensors indicate remaining lifetime higher than 40 years.
- Category 2: The total fatigue lifetime of substructures and subsystems in this category for all wind turbines is *at least* 22 years. This figure addresses the shear forces (F_z, F_y) along the main shaft as expressed in the rotating system (affecting the main shaft bearing(s) and the shaft/hub interface). The shortest lifetime regarding the blades' system is *at least* 23 years and addresses the shear force (F_z) at the hub-blade interface (affecting pitch bearings).