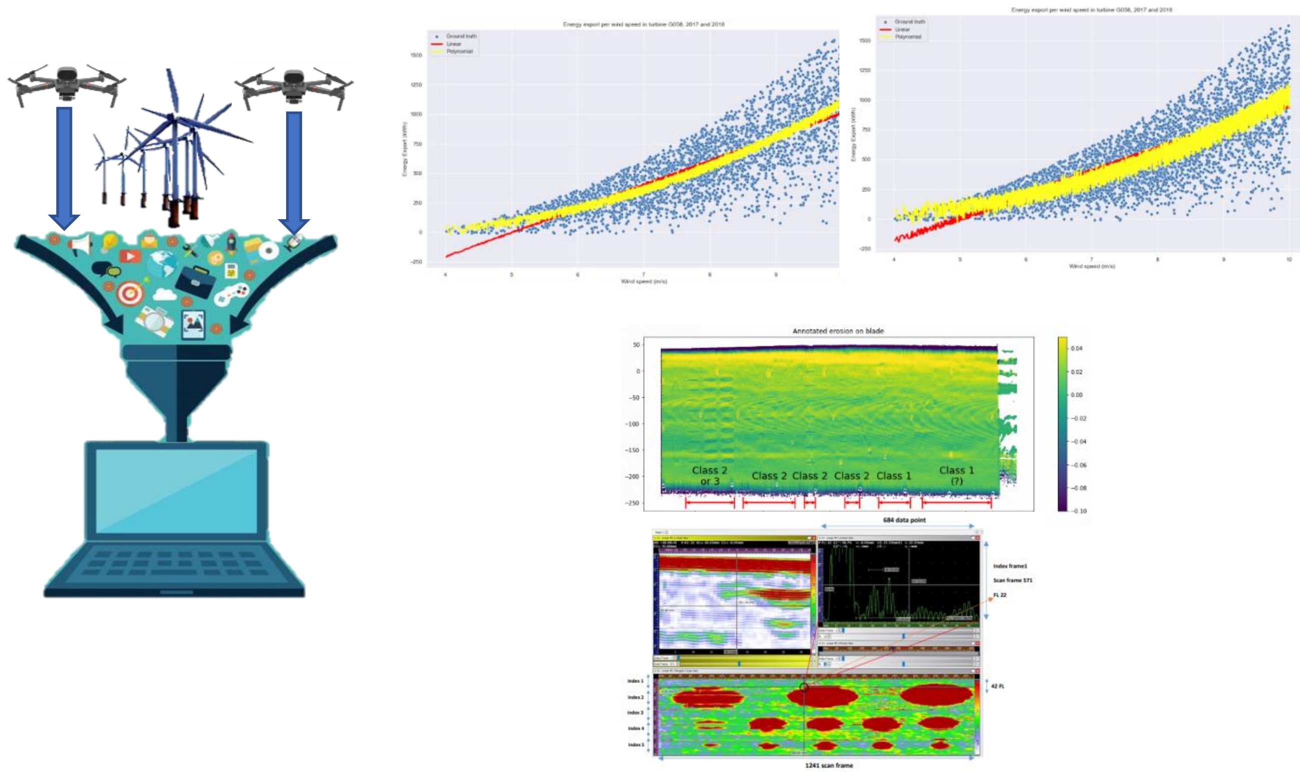
WP 4 Data Processing

WP Leader: Stork

Participants:

- Eneco
- TU Delft
- HZ
- Stork

Utilizing historical data and applying new sensor data



Introduction

Within the work package 4, research has been done for existing data and new generated data in order to collect, clean, enrich and store the data from the different data sources.

An inventory has been carried out of the current sources where information is collected and stored. The usability of data from these existing sources has been tested in relation to leading edge erosion (LEE). Information about the degree of predictability and identification of influence factors such as the position in the field, impact of Shells (protection against LEE) that must be taken into account. Data from new sensors were collected during testing and assessed for usability for modeling in WP6.

Objective/goal

The general goal of the WP4 is to collect, validate and prepare existing and new data for the use of modelling (WP6) and ultimately, the development of a business case (WP7).

To achieve this, the following sub-goals have been pursued:

- Explore all available data sources
- Test all data for usability for WP6 and WP7
- Clean data and enrich it if possible and necessary
- Save data in such a way that it can be used for further analysis

Way of working

The work package is divided into five different subtasks which are performed by all partners in the WP 4:

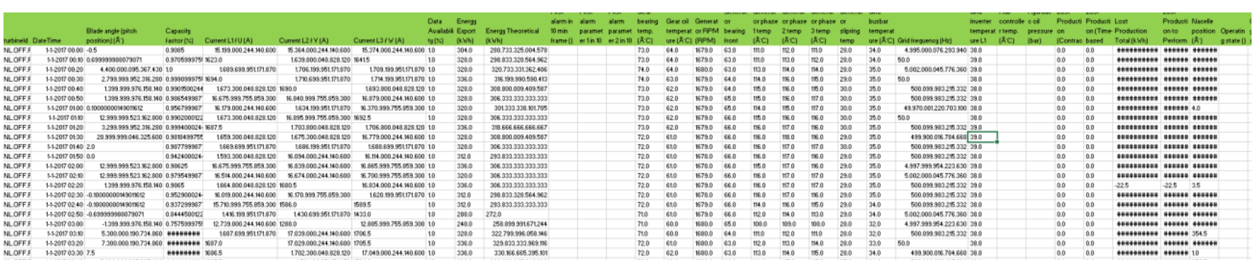
- WP 4.1 Multiyear, cleaned up dataset ready for processing: blade damage inspection data, performance (energy production data (on turbine level)
- WP 4.2 Clean dataset, aligned for modelling in WP6 with verified quality
- WP 4.3 Collection data from new sensors (1 year) of fully automated blade inspection data from off-shore wind turbines

Working procedure

WP 4.1 Multiyear, cleaned up dataset ready for processing: blade damage inspection data, performance (energy production data (on turbine level)

At first historical performance data has been collected. Eneco has provided 3 years of performance data from their Scada/DCS system Breeze for 3 Wind turbines: WTG30, WTG56 and WTG 58
These wind turbines were selected because of their different Leading Edge protection (fig 1).

WTG30 has a LEP9 coating, WTG56 has Polytech shells and WTG58 has a LEP9 coating but with some damages on it based on previous inspections.



turbineId	DateTime	Blade angle (pitch position) (Å˚)	Capacity factor (%)	Current L1 / U (A)	Current L2 / V (A)	Current L3 / W (A)	Data Availability (%)	Energy Export (kWh)	Energy Theoretical (kWh)
NL.OFF.F	1-1-2017 00:00	-0.5	0.9085	15.199.000.244.140.600	15.364.000.244.140.600	15.374.000.244.140.600	1.0	304.0	280.733.325.004.578
NL.OFF.F	1-1-2017 00:10	0.699999988079071	0.970599975	1623.0	1.639.800.048.828.120	1641.5	1.0	328.0	298.833.328.564.962
NL.OFF.F	1-1-2017 00:20	4.400.000.095.367.430	1.0	1.689.699.951.171.870	1.706.199.951.171.870	1.709.199.951.171.870	1.0	328.0	320.733.331.362.406
NL.OFF.F	1-1-2017 00:30	2.799.999.952.316.280	0.999099975	1694.0	1.710.699.951.171.870	1.714.199.951.171.870	1.0	336.0	316.199.990.590.413
NL.OFF.F	1-1-2017 00:40	1.399.999.976.158.140	0.990150024	1.673.300.048.828.120	1690.0	1.693.800.048.828.120	1.0	328.0	308.800.009.409.587
NL.OFF.F	1-1-2017 00:50	1.399.999.976.158.140	0.986549987	16.675.999.755.859.300	16.840.999.755.859.300	16.879.000.244.140.600	1.0	328.0	306.333.333.333.333
NL.OFF.F	1-1-2017 01:00	0.10000000149011612	0.956799987	16.179.000.244.140.600	1.634.199.951.171.870	16.370.999.755.859.300	1.0	320.0	301.333.338.101.705
NL.OFF.F	1-1-2017 01:10	12.999.999.523.162.800	0.990200012	1.673.300.048.828.120	16.895.999.755.859.300	1692.5	1.0	328.0	306.333.333.333.333
NL.OFF.F	1-1-2017 01:20	3.299.999.952.316.280	0.999400024	1687.5	1.703.800.048.828.120	1.706.800.048.828.120	1.0	336.0	318.666.666.666.667
NL.OFF.F	1-1-2017 01:30	20.999.999.046.325.600	0.981849975	1.659.300.048.828.120	1.675.300.048.828.120	16.779.000.244.140.600	1.0	328.0	308.800.009.409.587
NL.OFF.F	1-1-2017 01:40	2.0	0.987799987	1.669.699.951.171.870	1.686.199.951.171.870	1.688.699.951.171.870	1.0	328.0	306.333.333.333.333
NL.OFF.F	1-1-2017 01:50	0.0	0.942400024	1.593.300.048.828.120	16.094.000.244.140.600	16.114.000.244.140.600	1.0	312.0	293.833.333.333.333
NL.OFF.F	1-1-2017 02:00	12.999.999.523.162.800	0.98625	16.675.999.755.859.300	16.839.000.244.140.600	16.865.999.755.859.300	1.0	336.0	306.333.333.333.333
NL.OFF.F	1-1-2017 02:10	12.999.999.523.162.800	0.979549987	16.514.000.244.140.600	16.674.000.244.140.600	16.700.999.755.859.300	1.0	320.0	306.333.333.333.333
NL.OFF.F	1-1-2017 02:20	1.399.999.976.158.140	0.9865	1.664.800.048.828.120	1680.5	16.834.000.244.140.600	1.0	336.0	306.333.333.333.333
NL.OFF.F	1-1-2017 02:30	-0.10000000149011612	0.952900024	16.019.000.244.140.600	16.170.999.755.859.300	1.620.199.951.171.870	1.0	312.0	298.833.328.564.962
NL.OFF.F	1-1-2017 02:40	-0.10000000149011612	0.937299987	15.710.999.755.859.300	1586.0	1589.5	1.0	312.0	293.833.333.333.333
NL.OFF.F	1-1-2017 02:50	-0.699999988079071	0.844450012	1.416.199.951.171.870	1.430.699.951.171.870	1433.0	1.0	288.0	272.0
NL.OFF.F	1-1-2017 03:00	-1.399.999.976.158.140	0.757599975	12.739.000.244.140.600	1288.0	12.885.999.755.859.300	1.0	248.0	258.899.991.671.244
NL.OFF.F	1-1-2017 03:10	5.300.000.190.734.860	########	1.687.699.951.171.870	17.039.000.244.140.600	1706.5	1.0	328.0	322.799.996.058.146
NL.OFF.F	1-1-2017 03:20	7.300.000.190.734.860	########	1687.0	17.029.000.244.140.600	1705.5	1.0	336.0	329.833.333.969.116
NL.OFF.F	1-1-2017 03:30	7.5	########	1686.5	1.702.300.048.828.120	17.049.000.244.140.600	1.0	336.0	330.166.665.395.101

DateTime	alarm in 10 min frame ()	alarm parameter 1 in 10	alarm parameter 2 in 10	bearing temp. (Å˚C)	Gear oil temperature (Å˚C)	Generator RPM (RPM)	Generator bearing front	Generator phase 1 temp (Å˚C)	Generator phase 2 temp (Å˚C)	Generator phase 3 temp (Å˚C)	Generator slipring temp	busbar temperature (Å˚C)	Grid frequency (Hz)
1-1-2017 00:00				73.0	64.0	1679.0	63.0	111.0	112.0	111.0	28.0	34.0	4.995.000.076.293.940
1-1-2017 00:10				73.0	64.0	1679.0	63.0	111.0	113.0	112.0	28.0	34.0	50.0
1-1-2017 00:20				74.0	64.0	1680.0	63.0	113.0	114.0	114.0	28.0	35.0	5.002.000.045.776.360
1-1-2017 00:30				74.0	63.0	1679.0	64.0	114.0	116.0	115.0	29.0	35.0	50.0
1-1-2017 00:40				73.0	62.0	1679.0	64.0	115.0	116.0	115.0	30.0	35.0	500.099.983.215.332
1-1-2017 00:50				73.0	62.0	1679.0	65.0	115.0	116.0	117.0	30.0	35.0	500.099.983.215.332
1-1-2017 01:00				73.0	62.0	1679.0	65.0	114.0	115.0	117.0	30.0	35.0	49.970.001.220.703.100
1-1-2017 01:10				73.0	62.0	1679.0	66.0	115.0	116.0	116.0	30.0	35.0	50.0
1-1-2017 01:20				73.0	62.0	1679.0	66.0	116.0	117.0	116.0	30.0	35.0	500.099.983.215.332
1-1-2017 01:30				72.0	61.0	1679.0	66.0	116.0	118.0	116.0	29.0	35.0	499.900.016.784.668
1-1-2017 01:40				72.0	61.0	1679.0	66.0	116.0	117.0	117.0	30.0	35.0	500.099.983.215.332
1-1-2017 01:50				72.0	61.0	1678.0	66.0	116.0	117.0	116.0	29.0	35.0	500.099.983.215.332
1-1-2017 02:00				72.0	61.0	1678.0	66.0	115.0	117.0	116.0	29.0	35.0	4.997.999.954.223.630
1-1-2017 02:10				72.0	61.0	1679.0	66.0	116.0	117.0	117.0	29.0	35.0	5.002.000.045.776.360
1-1-2017 02:20				72.0	61.0	1679.0	66.0	116.0	117.0	117.0	29.0	35.0	500.099.983.215.332
1-1-2017 02:30				72.0	61.0	1678.0	66.0	116.0	117.0	116.0	29.0	35.0	500.099.983.215.332
1-1-2017 02:40				72.0	61.0	1679.0	66.0	114.0	116.0	115.0	29.0	34.0	500.099.983.215.332
1-1-2017 02:50				71.0	61.0	1679.0	66.0	112.0	114.0	113.0	29.0	34.0	5.002.000.045.776.360
1-1-2017 03:00				71.0	60.0	1680.0	65.0	108.0	109.0	108.0	28.0	32.0	4.997.999.954.223.630
1-1-2017 03:10				71.0	60.0	1680.0	64.0	111.0	112.0	111.0	28.0	32.0	500.099.983.215.332
1-1-2017 03:20				72.0	61.0	1680.0	63.0	112.0	113.0	114.0	28.0	33.0	50.0
1-1-2017 03:30				72.0	62.0	1680.0	63.0	113.0	114.0	115.0	28.0	34.0	499.900.016.784.668

DateTime	inverter temperature L1	controller temp. (Å˚C)	c oil pressure (bar)	Production (Contrac	Production (Time-based	Lost Production Total (kWh)	Production to Perform	Nacelle position (Å˚)	Operating state ()
1-1-2017 00:00	38.0			0.0	0.0	##########	######	######	
1-1-2017 00:10	39.0			0.0	0.0	##########	######	######	
1-1-2017 00:20	39.0			0.0	0.0	##########	######	######	
1-1-2017 00:30	38.0			0.0	0.0	##########	######	######	
1-1-2017 00:40	38.0			0.0	0.0	##########	######	######	
1-1-2017 00:50	39.0			0.0	0.0	##########	######	######	
1-1-2017 01:00	38.0			0.0	0.0	##########	######	4.0	
1-1-2017 01:10	38.0			0.0	0.0	##########	######	######	
1-1-2017 01:20	39.0			0.0	0.0	##########	######	######	
1-1-2017 01:30	39.0			0.0	0.0	##########	######	######	
1-1-2017 01:40	39.0			0.0	0.0	##########	######	######	
1-1-2017 01:50	38.0			0.0	0.0	##########	######	######	
1-1-2017 02:00	39.0			0.0	0.0	##########	######	######	
1-1-2017 02:10	38.0			0.0	0.0	##########	######	######	
1-1-2017 02:20	39.0			0.0	0.0	-22.5	-22.5	3.5	
1-1-2017 02:30	39.0			0.0	0.0	##########	######	######	
1-1-2017 02:40	38.0			0.0	0.0	##########	######	######	
1-1-2017 02:50	38.0			0.0	0.0	##########	######	######	
1-1-2017 03:00	39.0			0.0	0.0	##########	######	######	
1-1-2017 03:10	38.0			0.0	0.0	##########	######	354.5	
1-1-2017 03:20	38.0			0.0	0.0	##########	######	######	
1-1-2017 03:30	38.0			0.0	0.0	##########	######	1.0	

Figure 1 Sample of Breeze Data set

Eneco has also provided data form previous inspections done by rope access and gathered with photos taken by drones (fig 2) .This information is important to collect not only to prepare a business case but also to know in which conditions the 3 WTG are at the start of the 3 years of data and at the end.

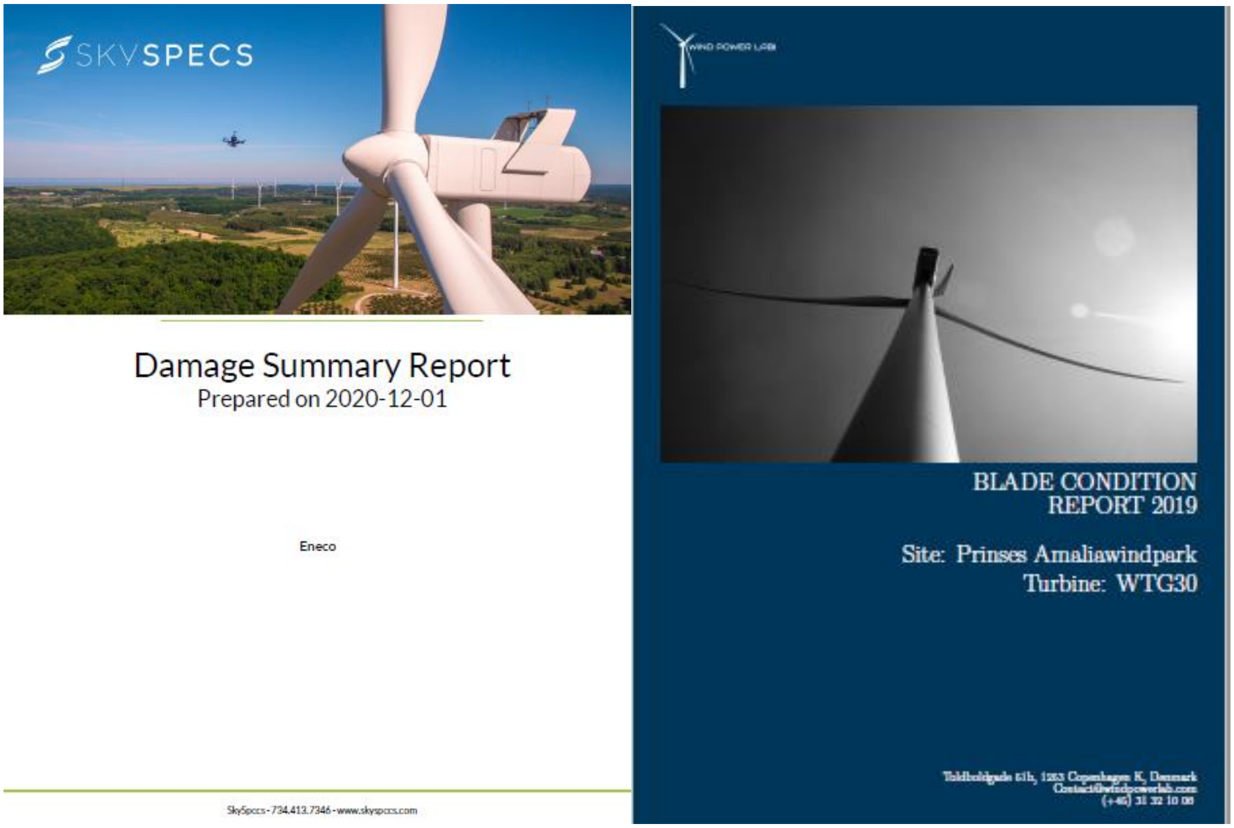
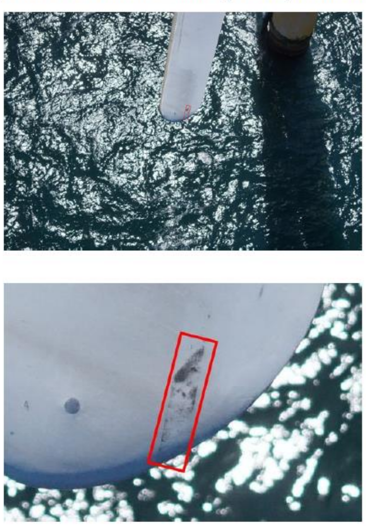


Figure 2 Reports form historical blade inspections on WTG30

Both operation data and maintenance data has been analyzed and discussed with Eneco. The way how the data is collected, the reliability of the available sensors and previous validation checks by Eneco were subjects that has been discussed and investigated.

Princess Amalia - WPQ7-56 | Discoloration - Severity 1



Turbine Information	
Manufacturer	Vestas
Model	V80
Latitude	52.5715810764286
Longitude	4.23179590357143
Hub Height	
Rotor Diameter	
Blade A Serial	51457 (Unconfirmed)
Blade B Serial	51578 (Unconfirmed)
Blade C Serial	51540 (Unconfirmed)

Damage Information	
Number	1HXD3VOX-0
Blade	B
Date	2020-05-29
Type	Discoloration
Width	0.052
Length	0.19
Subtype	Bugs / Dirt
Distance	40.7
Material	Surface
Severity	1
Component	Blade
Blade Side	Pressure Side
Inspection Date	2020-05-29
Inspection Time	05:26:48

Figure 3.Inspection data with Drone (photo) as existing inspection strategy.

WP 4.2 Clean dataset, aligned for modelling in WP6 with verified quality

Based in previous step data sets has been analyzed in more detail to be able to prepare it for later modelling.
At first the historical performance data from Breeze has been analyzed for the 3 WTG's. The data has been validated on 4 topics:

- Data quality check (Outliers, missing data points, anomalies)
- Impact shells on performance
- Impact LE or other damages on different locations on performance
- Impact position of WTG (ZOG)

There has been a selection form the Breeze data in consult with Eneco to mark the most important data points from the datasets needed for an initial validation. The data were selected in consultation with Eneco and used for the validation of the mentioned 4 topics. The table below shows the used data points.

0 turbineId	29 Lost Production to Performance (kWh)
1 DateTime	30 Nacelle position (°)
2 Blade angle (pitch position) (°)	31 Operating state ()
3 Capacity factor (%)	32 Operating sub state ()
4 Current L1 / U (A)	33 Pending Operating State ()
5 Current L2 / V (A)	34 Performance Index (%)
6 Current L3 / W (A)	35 Phase 1 temperature (°C)
7 Data Availability (%)	36 Phase 2 temperature (°C)
8 Energy Export (kWh)	37 Phase 3 temperature (°C)
9 Energy Theoretical (kWh)	38 Power Reference (kW)
10 First alarm in 10 min frame ()	39 Power factor (cosphi) ()
11 First alarm parameter 1 in 10 min frame ()	40 Production-based Contractual Avail. (%)
12 First alarm parameter 2 in 10 min frame ()	41 Production-based System Avail. (%)
13 Gear bearing temp. (°C)	42 Reactive power (kvar)
14 Gear oil temperature (°C)	43 Rotor inverter temperature L1 (°C)
15 Generator RPM (RPM)	44 Rotor inverter temperature L2 (°C)
16 Generator bearing front temperature (°C)	45 Rotor inverter temperature L3 (°C)
17 Generator phase 1 temp (°C)	46 Rotor speed (RPM)
18 Generator phase 2 temp (°C)	47 Time-based System Avail. (%)
19 Generator phase 3 temp (°C)	48 Top controller temp. (°C)
20 Generator slipring temp (°C)	49 Virtual Production (kWh)
21 Grid busbar temperature (°C)	50 Voltage L1 / U (V)
22 Grid frequency (Hz)	51 Voltage L2 / V (V)
23 Grid inverter temperature L1 (°C)	52 Voltage L3 / W (V)
24 Hub controller temp. (°C)	53 Wind direction (°)
25 Hydraulic oil pressure (bar)	54 Wind speed (m/s)
26 Lost Production (Contractual) (kWh)	
27 Lost Production (Time-based IEC B.2.2) (kWh)	
28 Lost Production Total (kWh)	

Table 1 Selected data point from Breeze

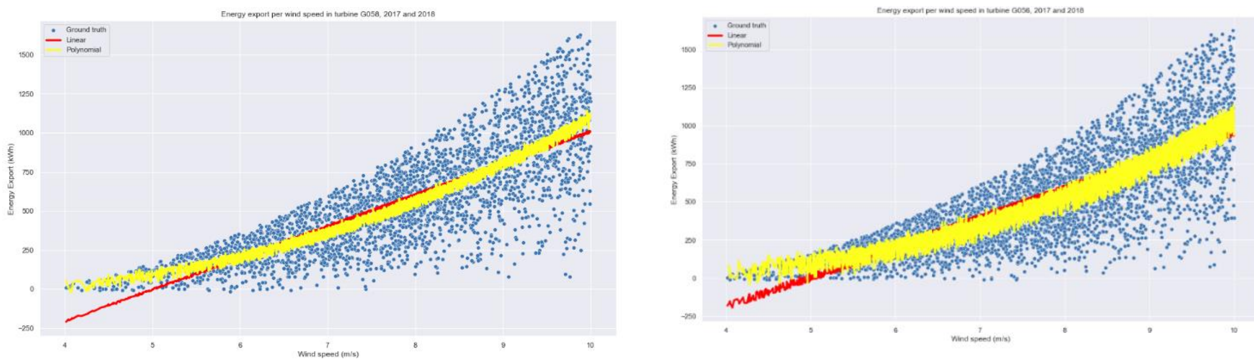
After cleaning, merging, corrections and removing unnecessary data the analysis on the Breeze data gives the following conclusions:

- Correlation between wind speed and energy export is very good, as expected.
- Used Data for 3 WTG's (3 years) showing no degradation in the years (less energy generating in time)
- Prediction of when inspection is needed for LEE based on historical performance data is not possible
- Need a lot of data for similar comparison
- Data quality was not at the level that was needed

The influence factors that has been investigated (ZOG, Seasons, coating etc.) were not visible in the analysis of the Breeze data. The main reason for this is that more data is needed

The Breeze data is generally not of a good enough quality to do this kind of analysis on. We started with some 470,000 rows. About 50% of all the resampled data was not usable. The energy export and blade pitch problems are especially worrisome.

Energy Export (KWh)



Wind speed (m/s) *Wind speed (m/s)*

Fig 4 With Shells *Without shell*

<u>WP 4.3 Collection data from new sensors (1 year) of fully automated blade inspection data from off-shore wind turbines</u>

Data from the following 2 new sensors were collected and tested:

- Laser Scanner (on Drone)
- Ultrasonic Sensor (on crawler)

This part has a direct link with the development and research of Sensor Packages (WP1). Different tests are performed in WP1 to select the sensors with the best specification and configuration. Representatives from TU Delft in WP4 were also involved in these testing activities. Requirements have been discussed and defined for data regarding format, storage method and communication protocols. The data from the new sensors were mainly produced with indoor tests. No frequent tests on Wind turbines onshore and offshore are performed. All tests are done on static blade samples.

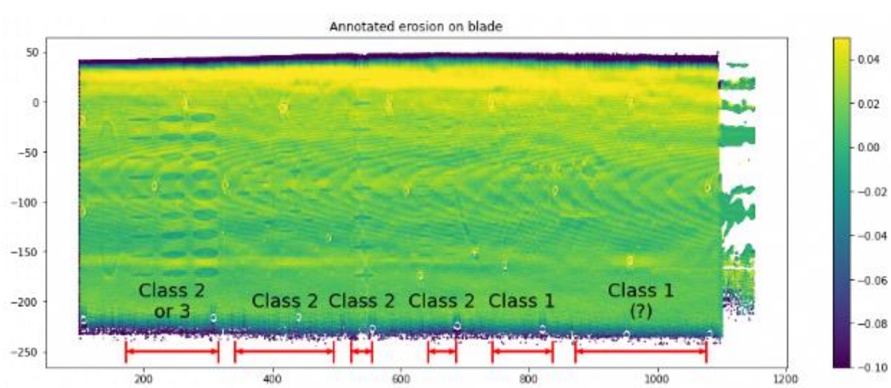


Figure 5. Laser Scanner: Automatic categorization of defects. Position indication of defects.

.

For the laser scanner the data is usable for further modelling e.g. the automatic classification (see fig. 6) of defects and indicating the position of the defects on the blade. This data is stored on a SD card.

CATEGORY	DAMAGE	ACTION	TURBINE
1	Cosmetic Readings of lightning system below 50mΩ	No need for immediate action	Continue Operation
2	Damage, below wear and tear	Repair only if other damages are to be repaired	Continue Operation
3	Damage, above wear and tear Readings of lightning system above 50mΩ	Repair done within next 6 months	Continue Operation
4	Serious damage	Repair performed within next 3 months. Damage monitored	Continue Operation
5	Critical damage	Immediate action required to prevent turbine damage. Contact technical support	STOP Operation safety is not ensured

Figure 6. Classification categories for blade damages

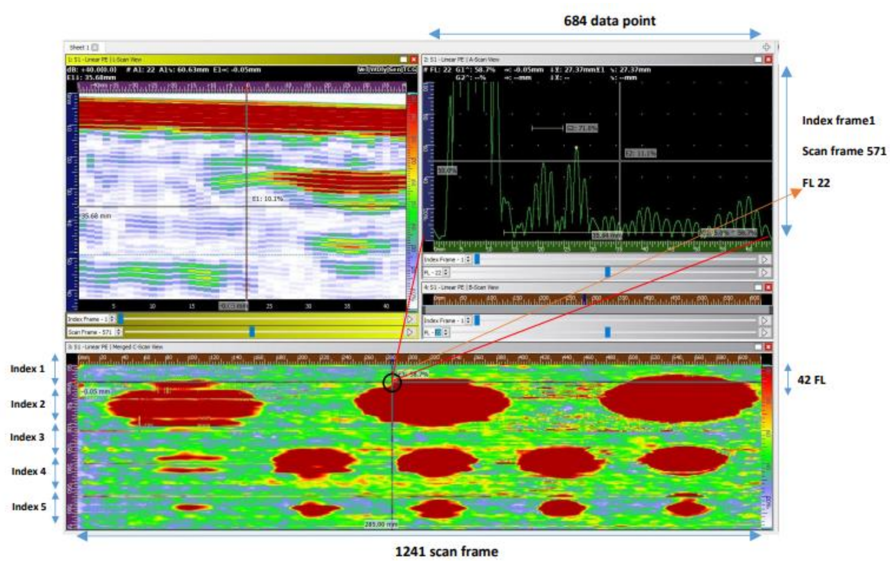


Figure 7. Ultrasonic Sensor: Positions and size of structural damages

For the Ultrasonic Sensor special software is used for identification of internal damages. A diagnostic engineer is needed to indicate the size and the position of the failure. With some sophisticated rules it is expected to automate the diagnosis.

Data from both sensors is good quality and usable for further modelling.

Deliverables.
The following deliverables have been provided:

- Inventory of available sources (operation and maintenance)
- Data collection from available sources (existing information from Breeze) and new data from the Sensors
- Analysis of Breeze data (integrated in WP5) according to validation criteria, usability, validation on quality
- Validation of existing data on predictability, trends, influence factors (position in the field, degree of LEE)
- Alignment in the definition of requirements for new data

Conclusion and recommendations
The main conclusions and outcomes of the WP4 are:

- Historical data from SCADA system Breeze is limited usable for indicating LEE based on performance or other combination of registrated sensor data.
- No reliable lead time can be produced from Breeze data, modelling degradation for indication when to plan a repair campaign.
- Historical data from Breeze needs a lot of cleaning and correction due to not reliable wind sensors (direction and speed) and outliers or data gaps.
- For comparison studies showing impact of influence factors (ZOG, seasons of the year, coating, and the use of protecting shells) 5 years of data is needed as a minimum.
- Historical maintenance data is available in reports and needs translation towards data sets for an easy comparison and indicating trends.
- Historical maintenance data is excellent input for the baseline definition (Current maintenance strategy) for WP7.
- The laser scanner data can be used for storing size and position of blade damages. Therefore data is usable for automatic classification of blade damage.

<u>Recommendations</u>
For an improved prediction of LEE historical data is very important. This data must be used to learn from to get an early warning from trends or with the help of Machine Learning.
Previous studies has shown that performance data can be used for an early indication of degradation of the blades.
For this the following recommendation are given:

- Improve the reliability of sensors on the Wind turbine (pitch, wind speed and direction)
- Improve data registration by introducing automated data validation checks on the Breeze data
- Introduce a digital twin were data sources are integrated and data is stored in a central data lake.
- Defining performance dashboards based on smart rules indication the health of the blades (see also fig 9)

Data should be collected on a frequent base in order to produce trends, detect anomalies and even give a prediction of the lead time of a failure. Drone inspection with laser scanner should be done at least once a year to be able to see the characteristics of LEE.
The classification is now possible but a lot of added value is given by identifying the degradation characteristics. Collecting data more frequent enables a better prediction of the degradation.

The data from the ultrasonic sensor is analyzed by software. The diagnostics should be automated and stored in a usable format (CSV) to be able to identify the degradation characteristics.

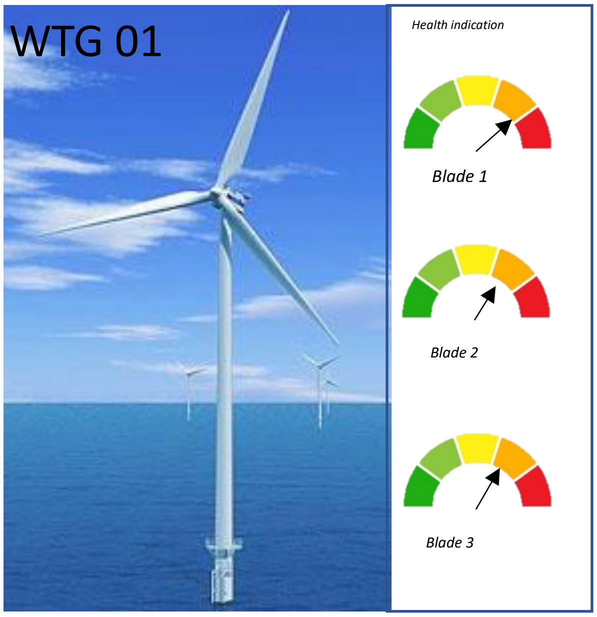


Figure 8. Example dashboard Blade Health Indication