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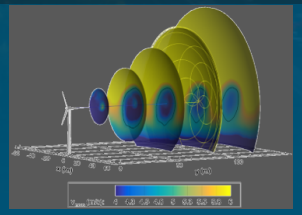
Using Low Fidelity Simulations To Predict and Reduce Field Experiment Uncertainty



PRESENTED BY

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U.S. DEPARTMENT OF ENERGY NNSA

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Field testing is hard

- Field testing is critical to validation of wind turbine designs
- Field testing can have high uncertainties due to many sources of error, both random and bias
- What if you're looking for small differences between the two rotors, e.g., an increase in power of ~4%?
- But the uncertainty of differences is larger than the uncertainty of individual measurements…

So how much data, or how long, do you need to ensure you obtain significan

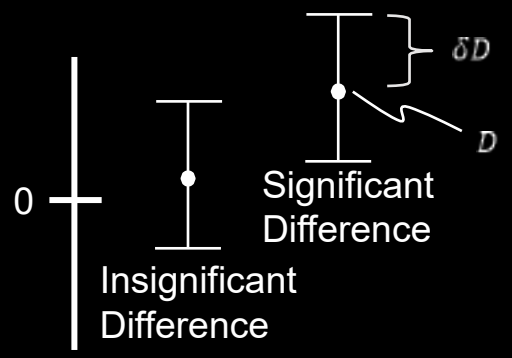
Uncertainty in Control and Treatment

$$D = P_1 - P_2$$

$$\delta D = \sqrt{\delta P_1^2 + \delta P_2^2}$$

If $\delta P_1 \approx \delta P_2$, then

$$\delta D = \sqrt{2}\delta P_1 \approx 1.4\delta P_1.$$



For example, if we expect

$$P_1 = 1.04P_2,$$

then

$$D = 0.0385P_1,$$

which means that, to be significant

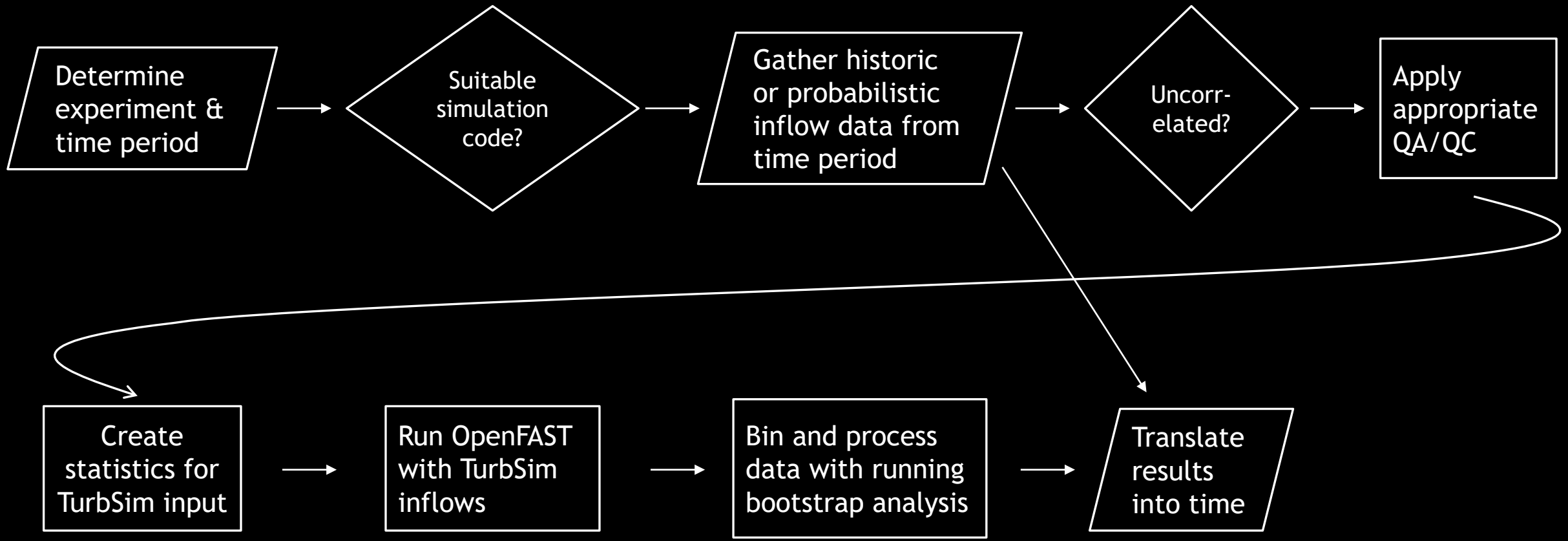
$$\delta D < 0.0385P_1$$

This in turn means that

$$\delta P_1 < 0.0272P_1,$$

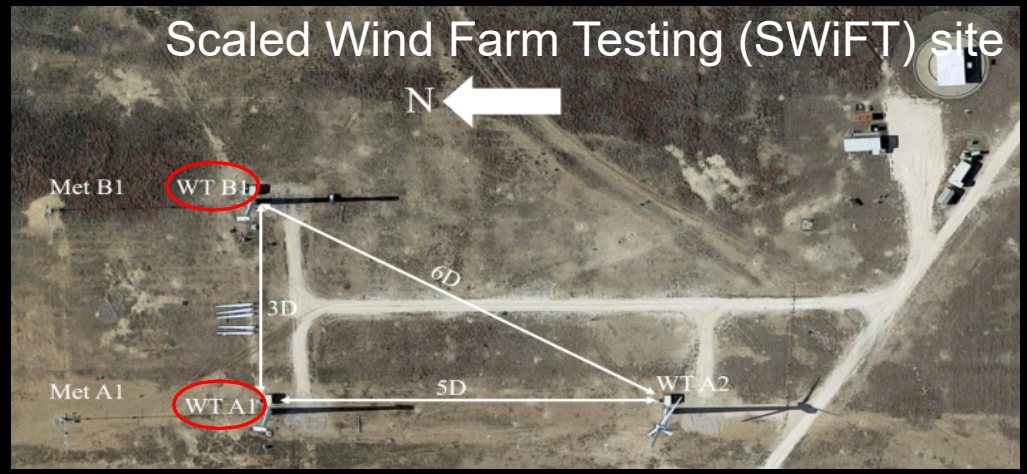
which is probably a difficult level of accuracy to achieve.

Method


Determine experiment & time period
Suitable simulation code?
Gather historic or probabilistic inflow data from time period
Uncorr-elated?
Apply appropriate QA/QC
Create statistics for TurbSim input
Run OpenFAST with TurbSim inflows
Bin and process data with running bootstrap analysis
Translate results into time

Predicting the Uncertainty of an Experiment

- Scaled Wind Farm Test (SWiFT) site has three modified V27 wind turbines
- WT A1 and WT B1 are sited to allow for simultaneous control and treatment testing

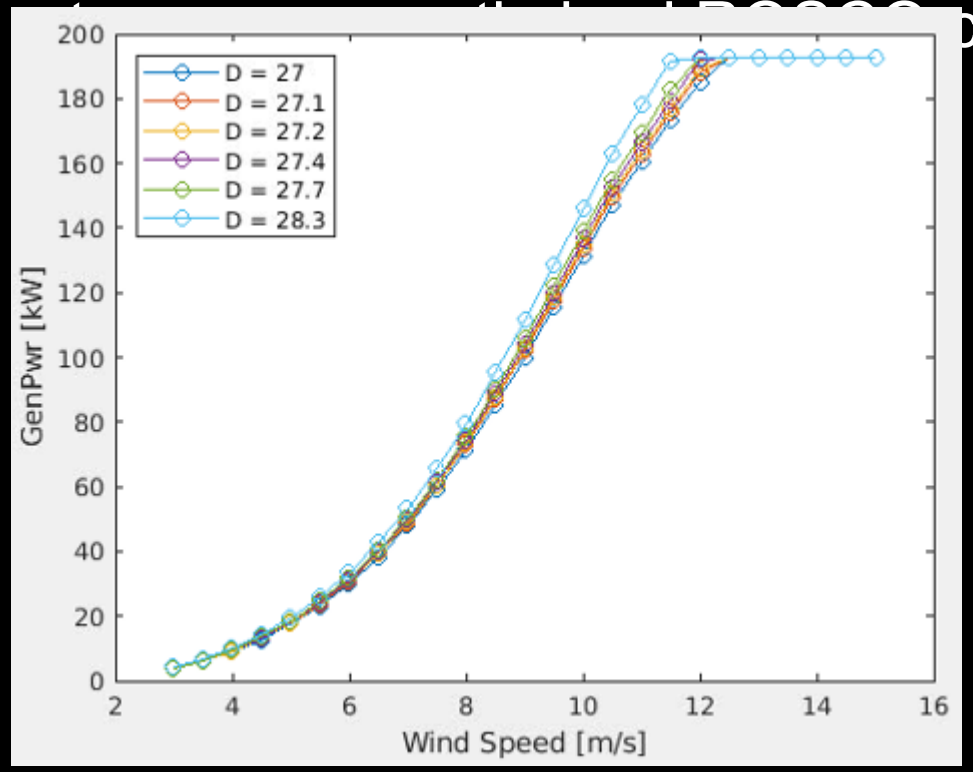


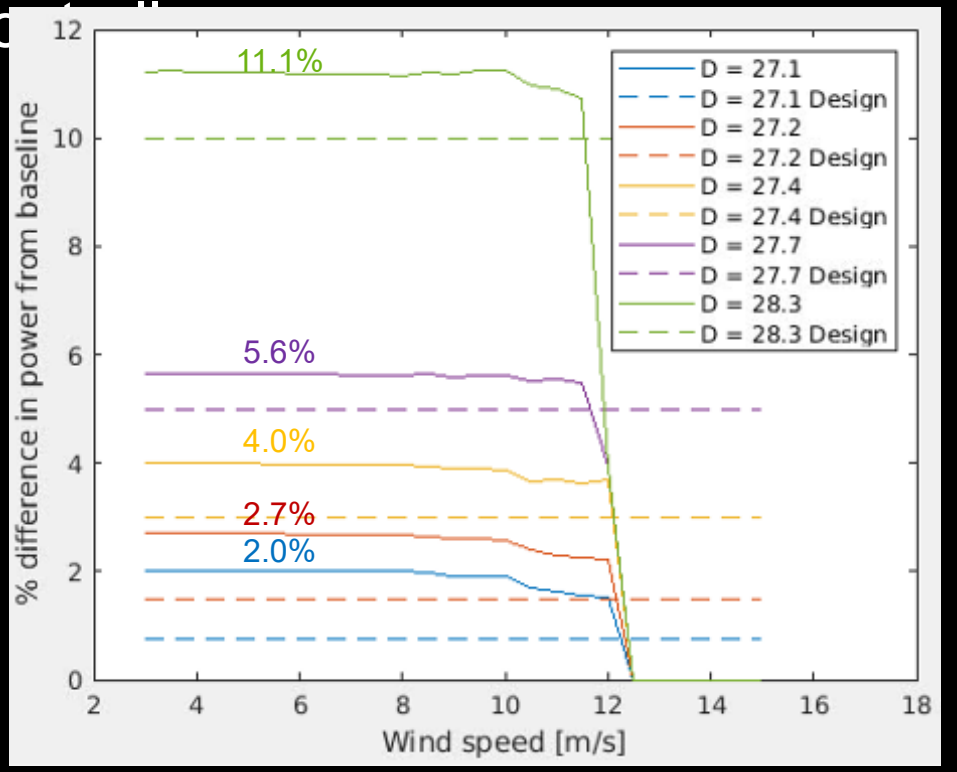
- Use OpenFAST (turbine modeling) with TurbSim (inflow modeling)
- Use data from SWiFT site (wind speed, TI, shear) as TurbSim inputs
- Simulate baseline V27 and a series of tip extensions to produce more power ($P \sim A$)

D [m]	27	27.1	27.2	27.4	27.7	28.3
Expected power gain [%]	-	0.75	1.5	3	5	10

Rotor Tip Extensions

- Tip extensions were derived from linear extrapolation of blade properties (chord and twist)
- They were designed *only* to produce a particular power increase based on rotor area
- All





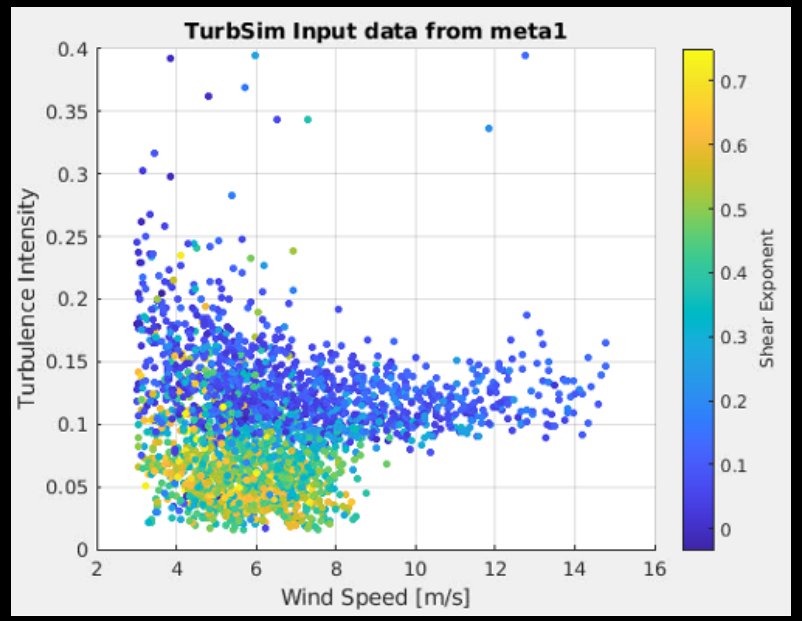
Setting Up TurbSim

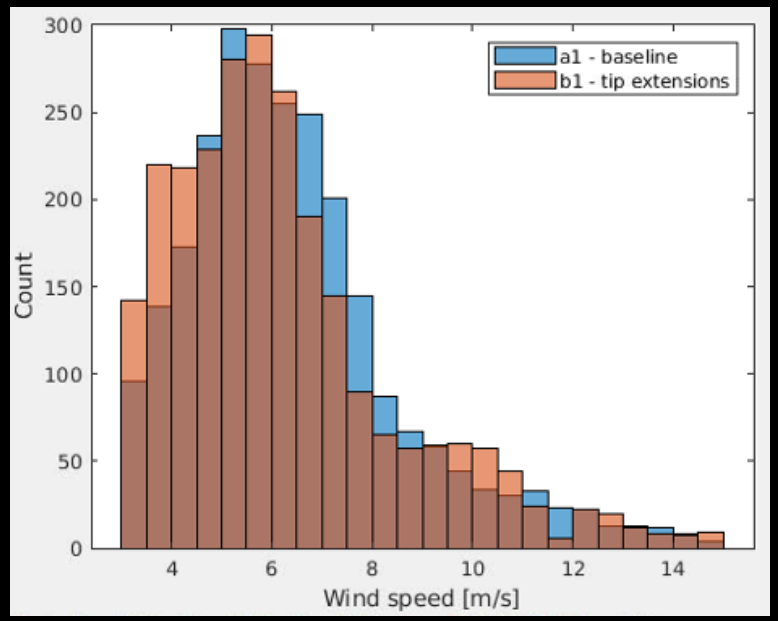
- TurbSim needs hub height wind speed, TI, and shear exponent as inputs
- SWiFT site met data resources:
  - ~1.5 years of TTU met tower data (was used for site characterization),
  - lots of a1 met tower data, and
  - some b1 met tower data

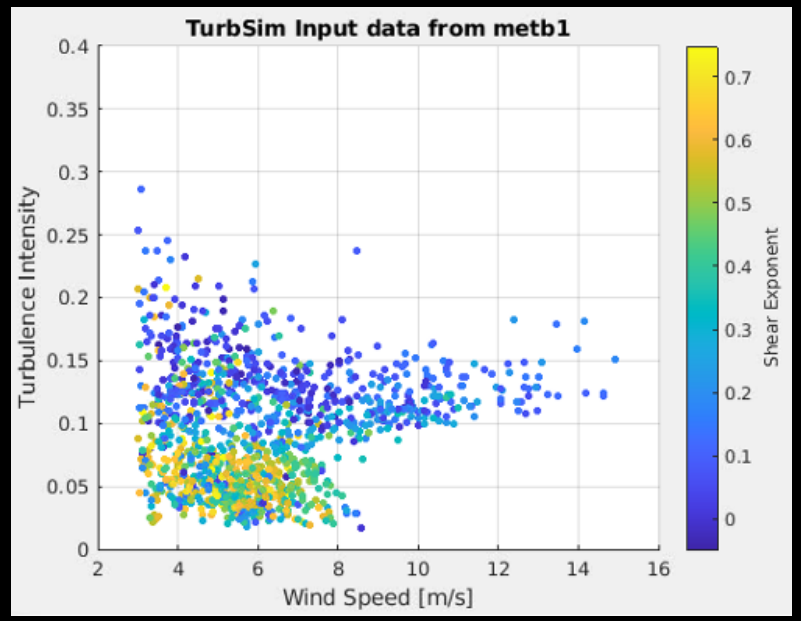
Steps:

1. meta1 and metb1 data filtered for working hours and expected months of experiment over multiple years and make 10 minute bins
2. Results of site characterization used to threshold this data (high level QA/QC)
3. Check that 10 minute bins are uncorrelated
4. To get 2520 10 minute bins
   1. Randomly downsample meta1
   2. Randomly upsample metb1 with replacement
5. Stats from each 10 minute bin are inputs to one TurbSim inflow, which is one simulation, which represents one 10 minute sample of field data

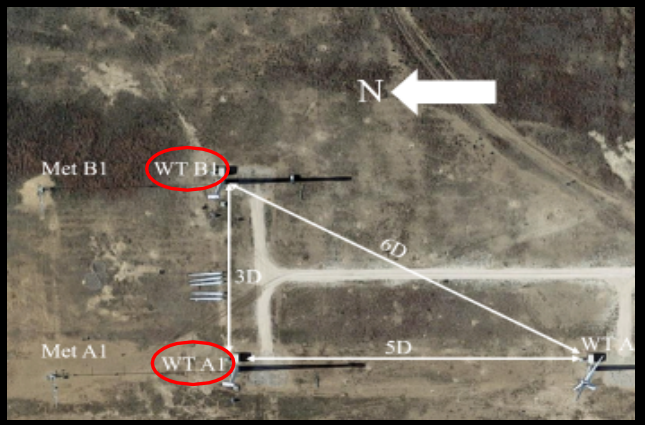
TurbSim Input Data from Met Towers



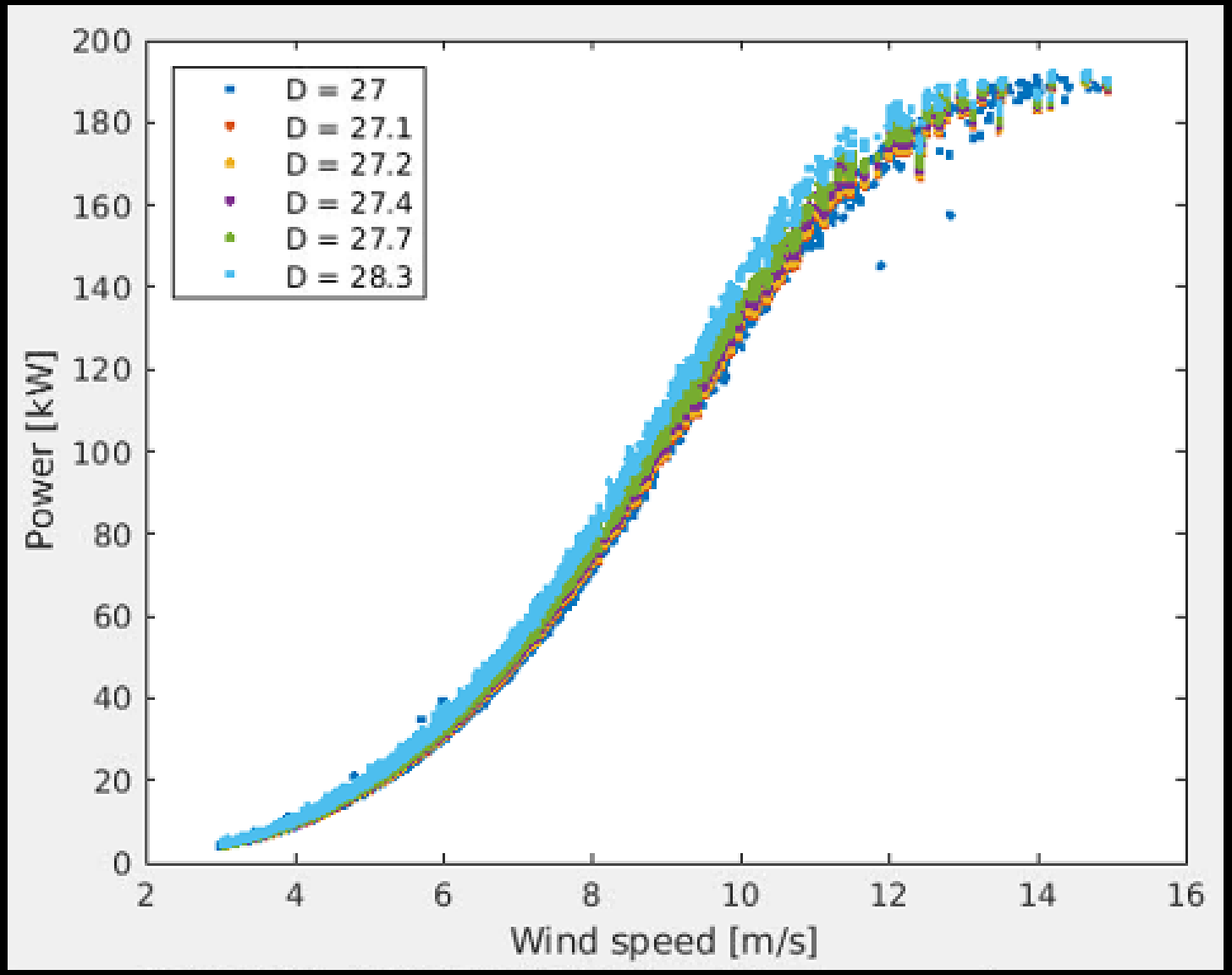




- High variability at low wind speeds
- Low number of high wind speed observations
  - May not be converged
  - May not support robust bootstrap analyses
- Clear mismatch between observations from a1 and b1 at some wind speeds

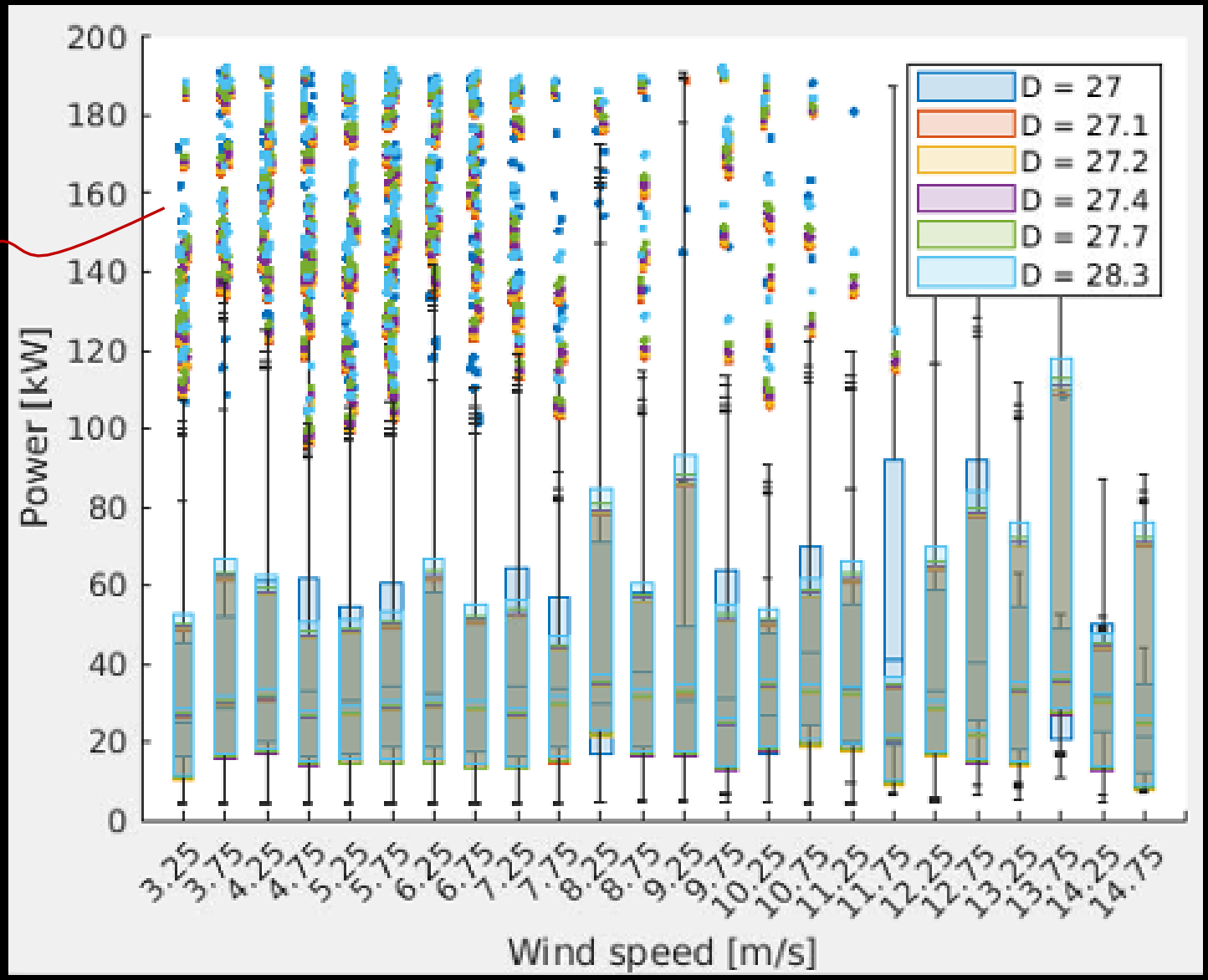


Results – Focus on Power

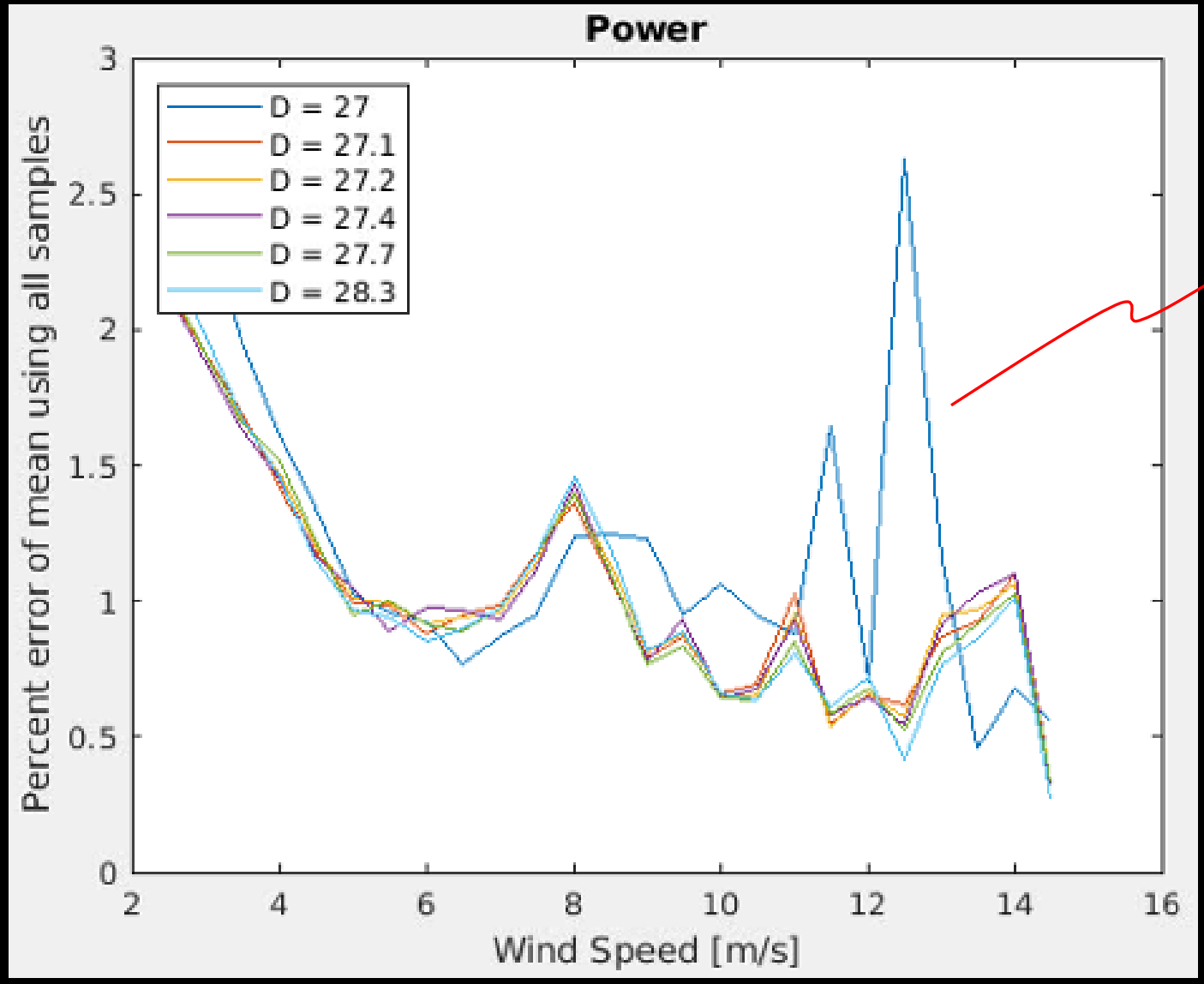


Results – Boxplot of Power

Long tails

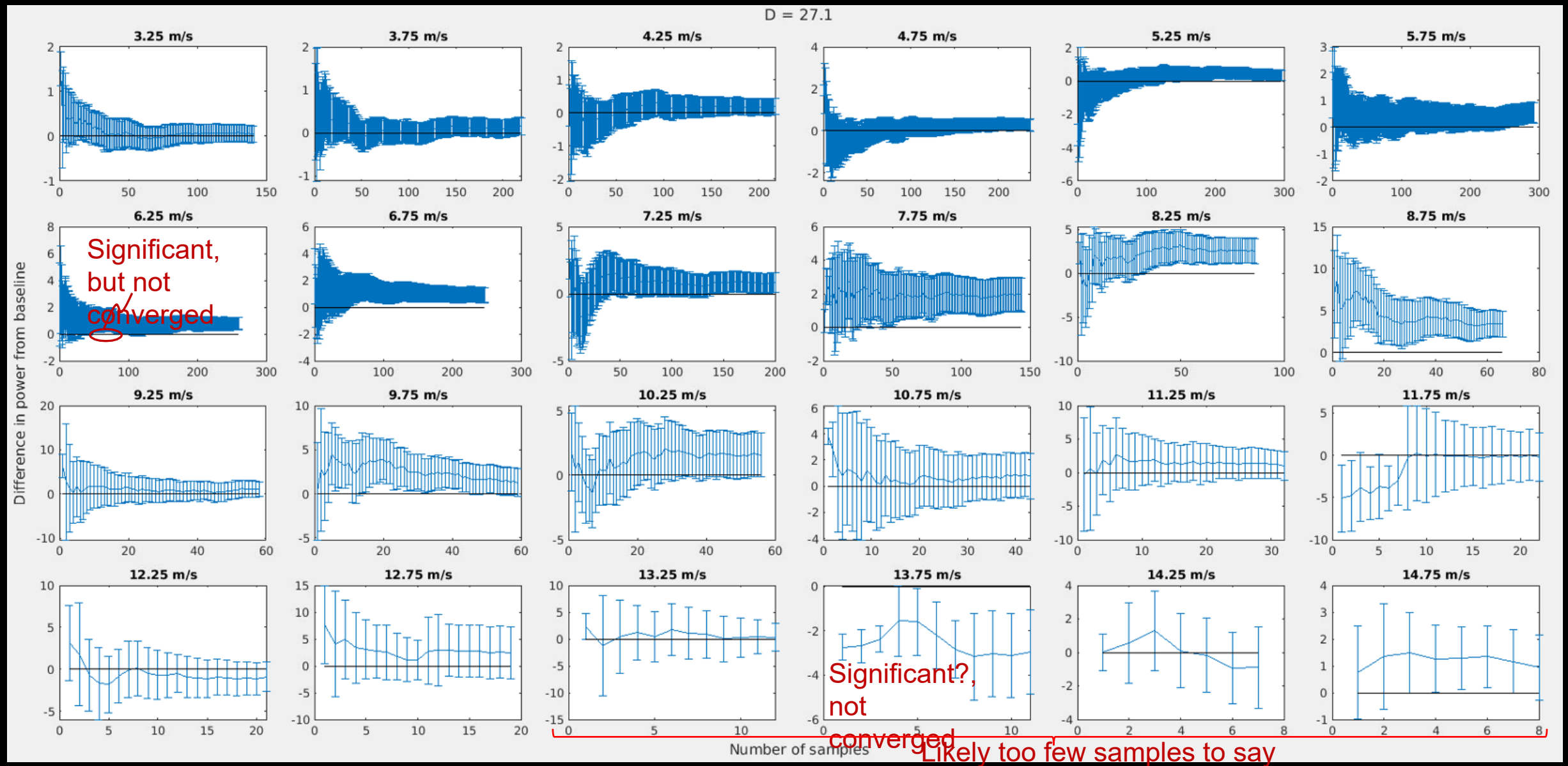


Results – Random Errors within Bins

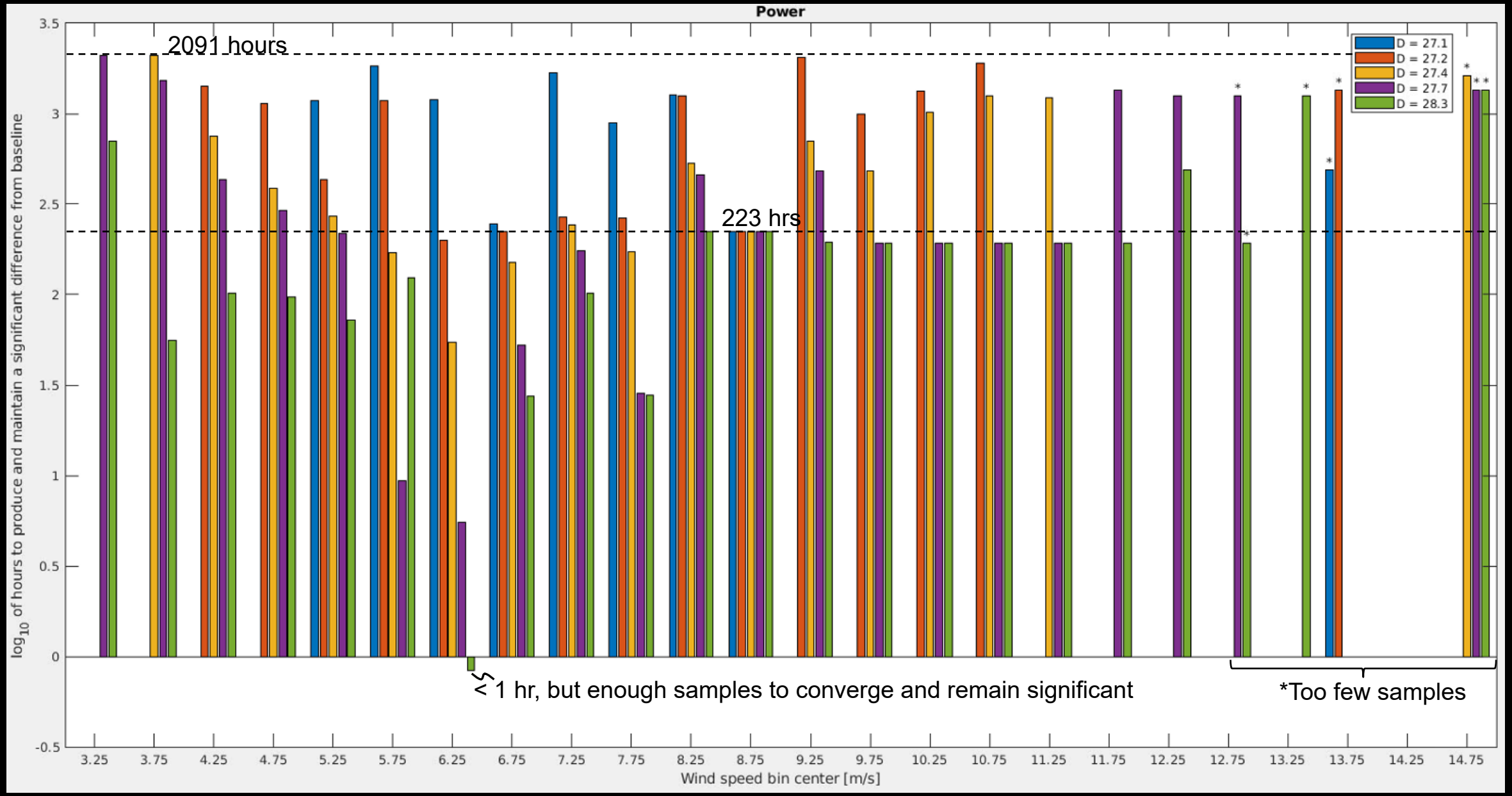


Recall low number of observations at high wind speeds. Bootstrap analysis may not be valid.

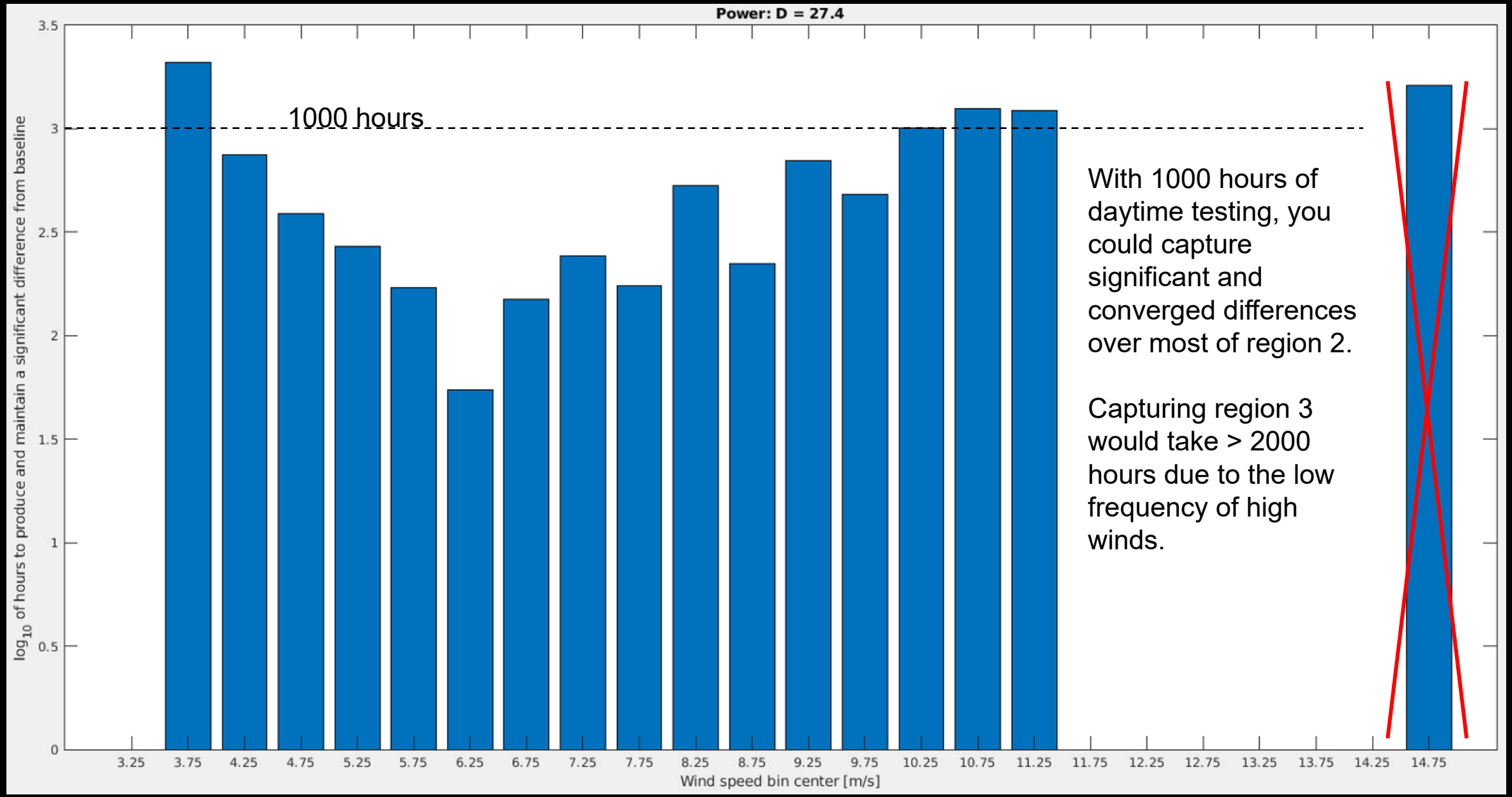
Results – Significant vs Converged



Results – Significant Differences by Time



Results – Example: 4% expected difference



Conclusions

- Within the accuracy of the simulations, this methods allows you to
  - Predict the individual measurement uncertainties of wind turbine field experiments
    - Bias errors can be incorporated as desired in post-processing
    - Random errors can be computed through bootstrap analyses on the simulated data
  - Predict the uncertainties of differences in control and treatment experiments
  - Estimate the time required to reach acceptable levels of uncertainty
- The method requires
  - An appropriate simulation method suitable for thousands of simulations
  - An appropriate wind turbine model
  - A dataset of inflow conditions
    - Historical met tower data from the test site is best
    - Could use probabilistic models of inflow conditions

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Thanks!

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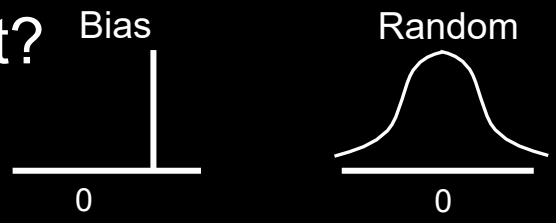
Quick Refresher on Uncertainties

What determines the uncertainty of a measurement?



Uncertainty comes from bias and random errors. In context…

Bias errors will probably be from differences in inflows if measurements are not simultaneous and more or less co-located and from any differences in the turbines if we use two. Bias errors may be mitigated by binning data to compare similar conditions.

If you can say the “same” experiment was done for the control and treatment, then bias errors are equal and subtract to a negligible magnitude when looking at differences.

Random errors will primarily come from the inflow.

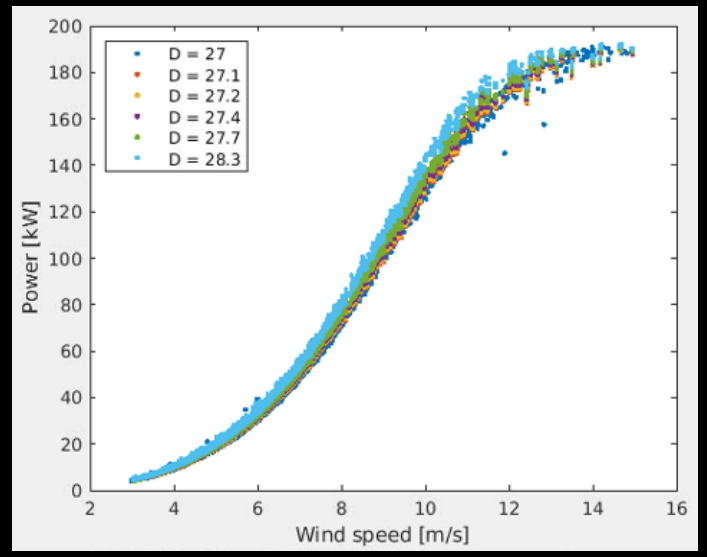
They can be quantified using a bootstrap technique and can be minimized by ensuring the data set is long (in time not number of points) enough.

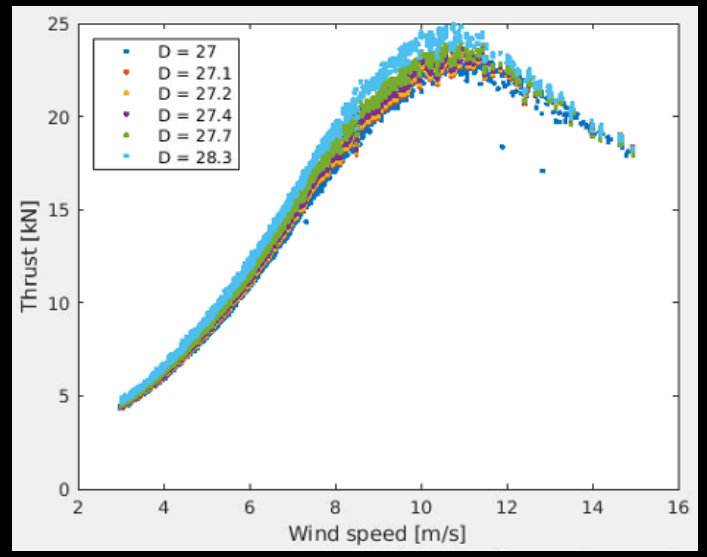
	Sequential testing	**Simultaneous testing**
Bias errors	Potentially large differences in inflows	Probably small differences in turbines and inflow
Random errors	From inflow, but not same	From inflow, but probably same

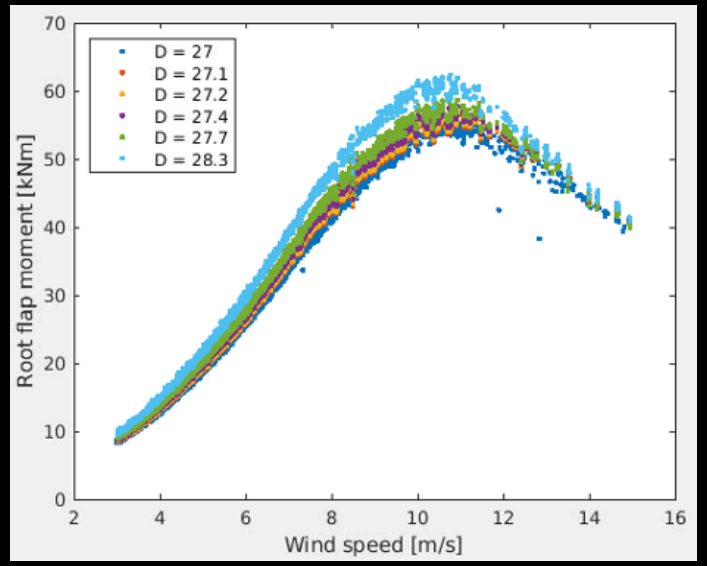
Planning a control and treatment experiment

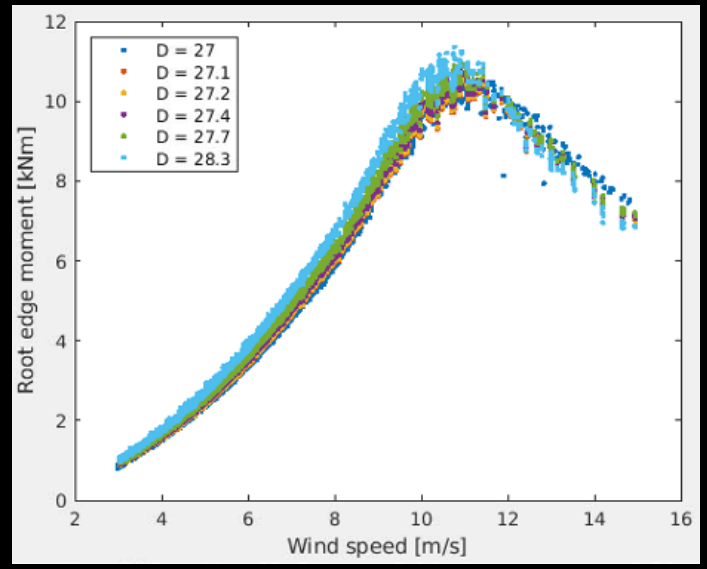
- What quantities of interest (QoI) do we care about most?
  - Power, thrust, blade root bending moments
- What size differences do we expect in those QoI between the control and treatment?
  - TBD, but all small
- What uncertainty do we expect in the measurement of those QoI?
  - TBD and depends on method, but possibly large
- How does the amount of data affect the uncertainty?
  - Will definitely reduce random error and more data will allow for finer binning to reduce bias error
- How does this ultimately influence how we should conduct the field test to achieve significant differences in the QoI?
  - May tell us how long to test and/or that it would be better to focus on certain conditions

Results – All QoI across Wind Speeds



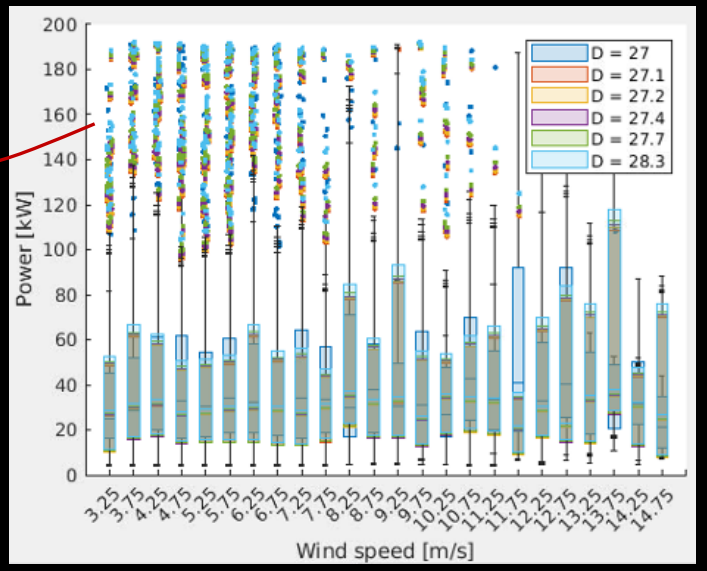


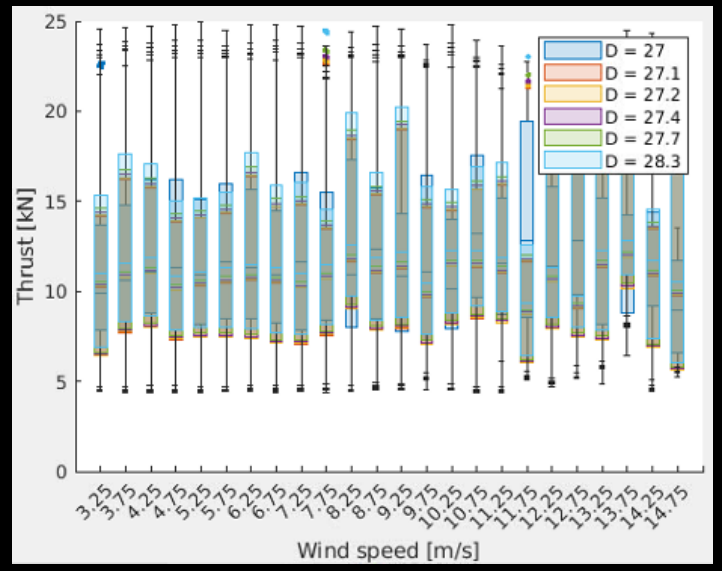


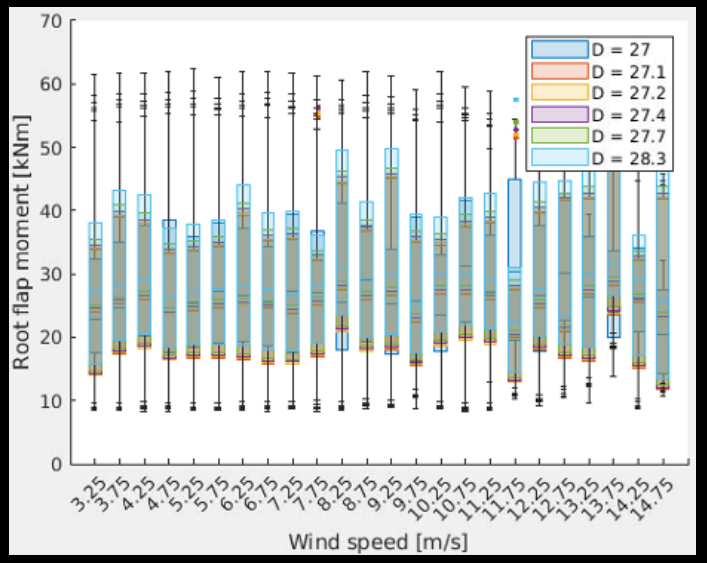


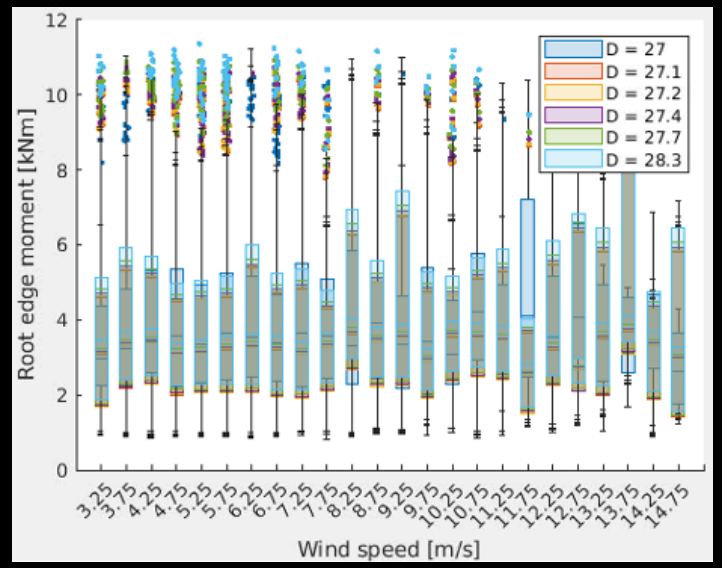
Results – Boxplots of QoI across Wind Speeds

Long tails

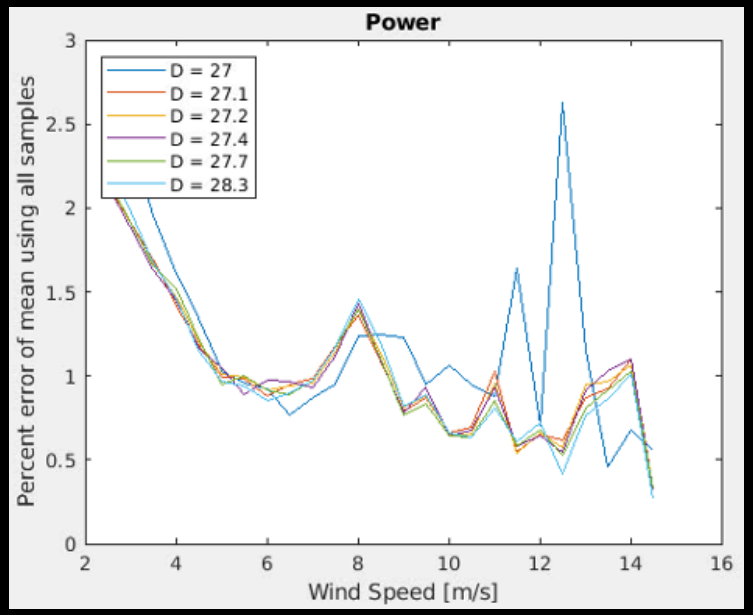


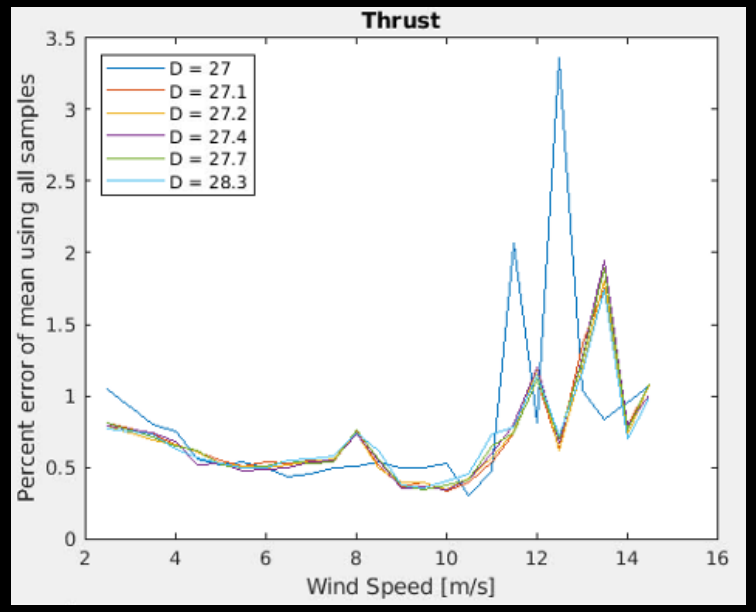


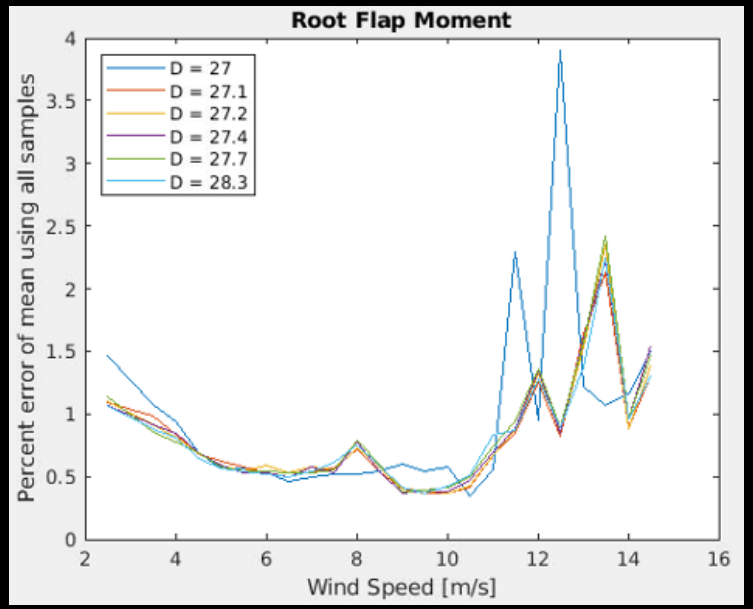


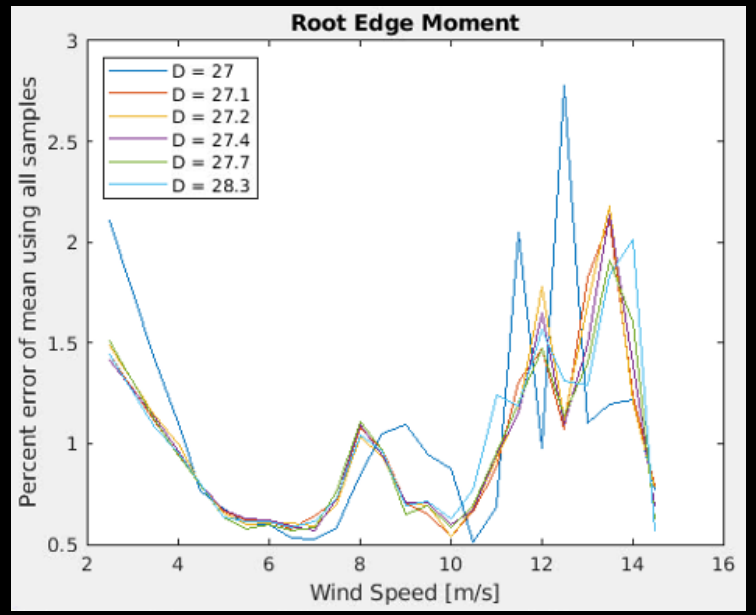


Results – Random Errors

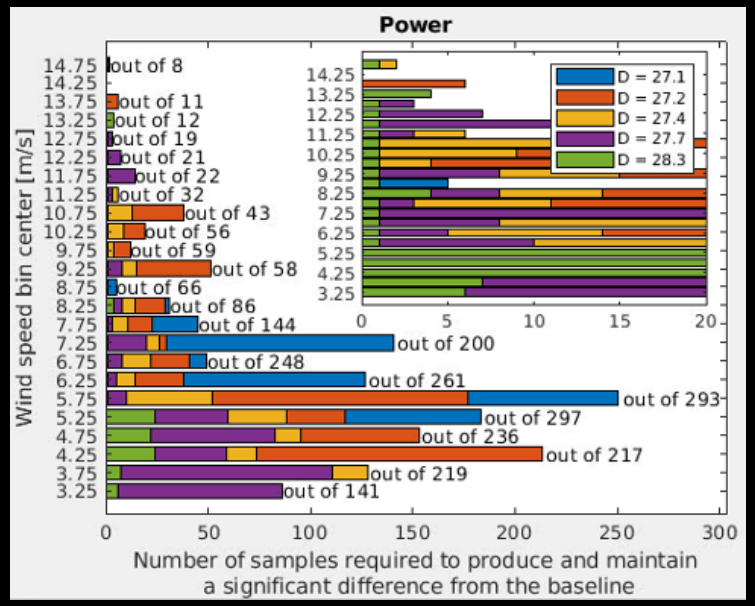


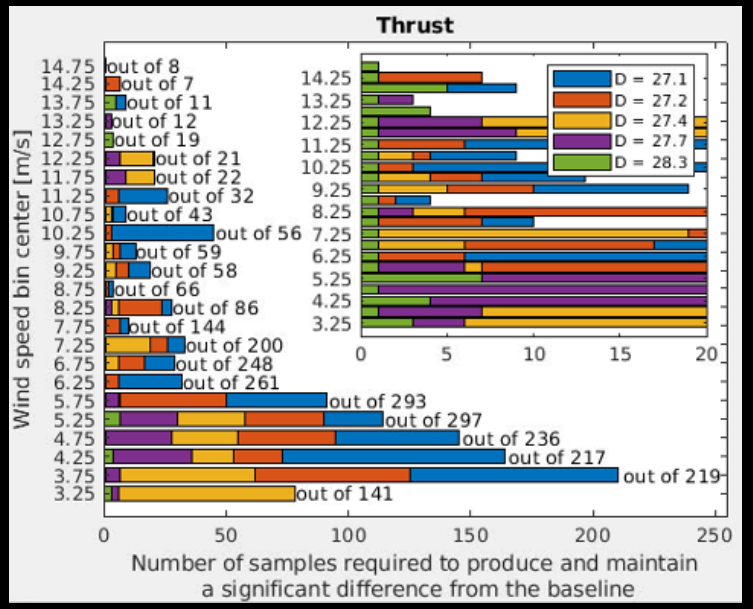


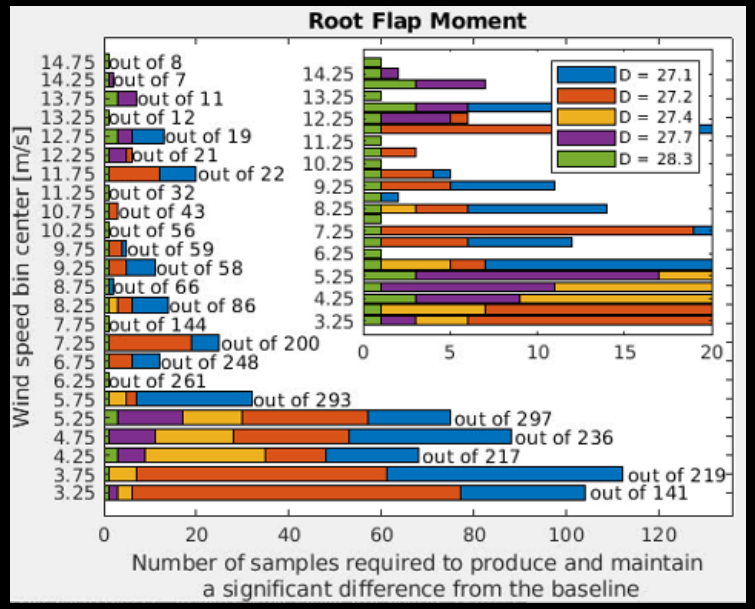


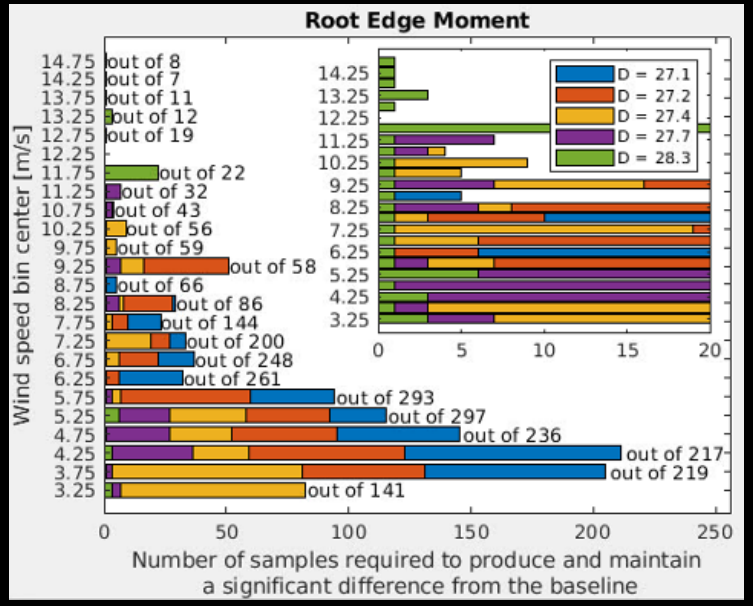


Results – Significant Differences by Samples









Results – Significant Differences by Time