Application of Systems Engineering to Wind Farm Design

A Focus on Meteorology & Tools

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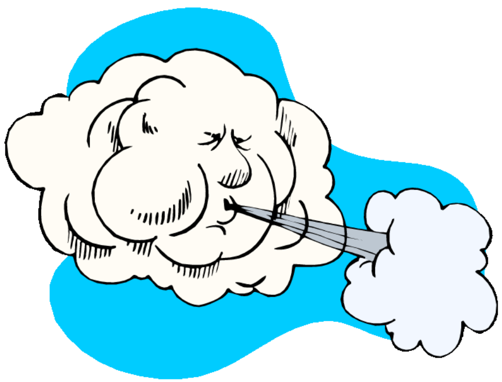
Wind goes in, money comes out!



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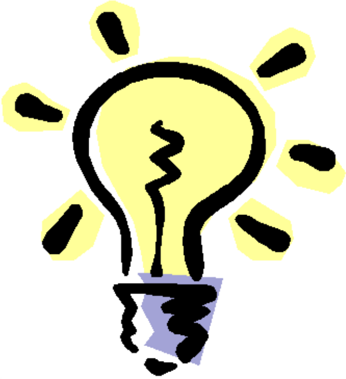
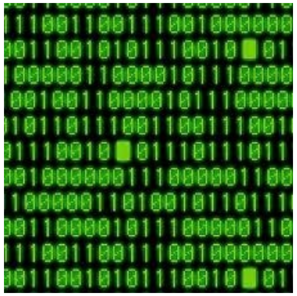
Don't forget the other externals

Other Weather

Snow & Ice



Electricity



Data

Overview

Systems Engineering

- Analyzing Customer Needs/Requirements
- Design Synthesis

Meteorology

- Geography – where's the windiest spot near a given market opportunity?
  – Define a project boundary
  – Estimate NCF
- Design preliminary turbine array and observation campaign
  – Internal Constraints Analysis
  – Site suitability
  – Near-site surface data

Overview (Continued)

Systems Engineering

- Design Validation & Iteration

Meteorology

- Meteorological Observation & Modeling
  - Observations: MET towers, Sodar, Lidar
  - Long Term Data
  - Spatial Models: WAsP / WindFarmer / WRF/OpenFOAM
  - Internal Control Documents (ICDs) provide consistency as well as dictate project advancements & milestones

Overview (Continued)

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Systems Engineering

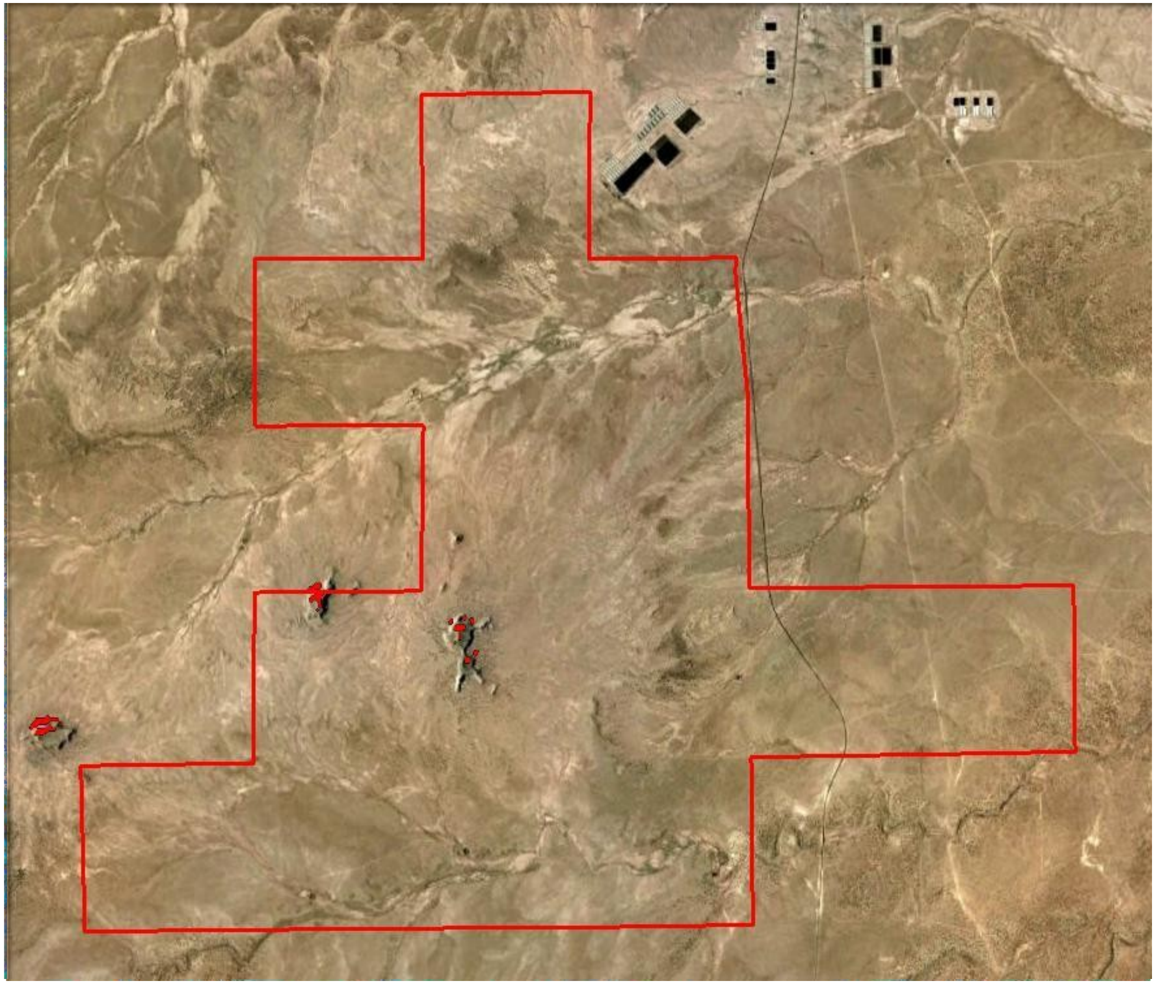
- Iteration & Tradeoff analysis
- Construction
- Operations

Meteorology

- Evaluate production & maximize
  - Rough crosswind / downwind spacing
  - Individual turbine placement
  - Analysis of complex turbine / terrain interactions
  - Implementation of lessons from operations
- Identify root cause of excessive faulting or failures
  - Due to meteorological conditions
  - Due to complex interactions

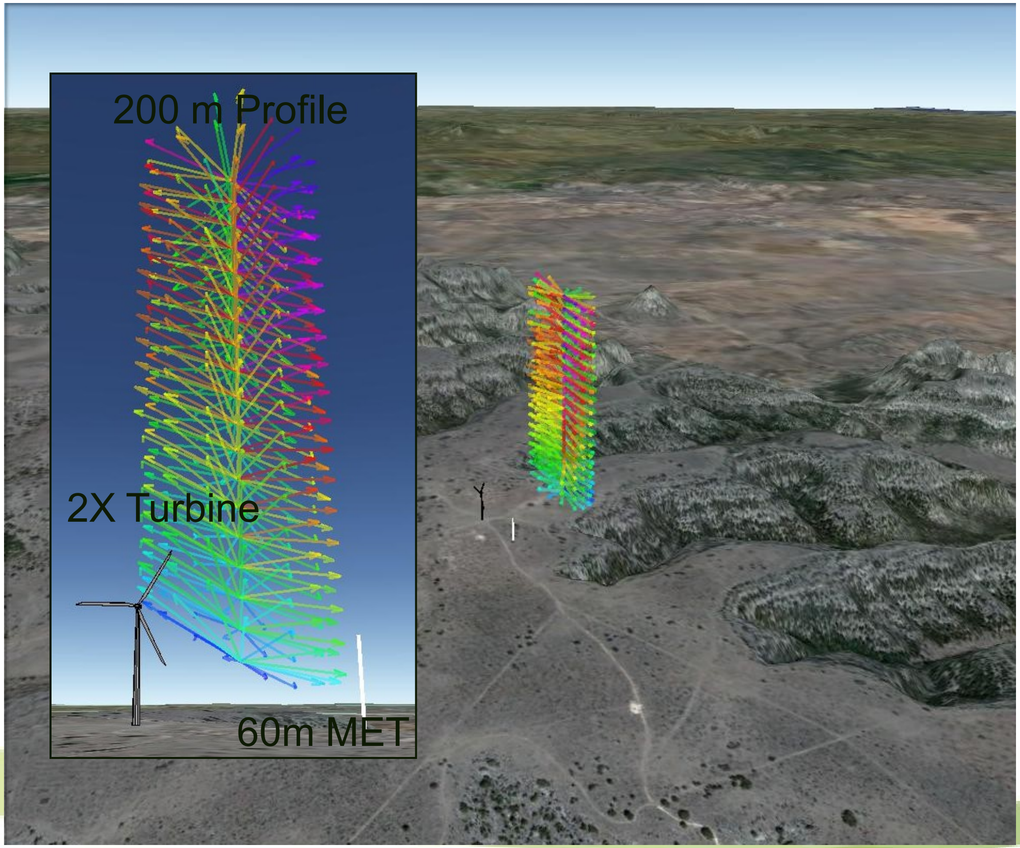
Tools (Early Stage)

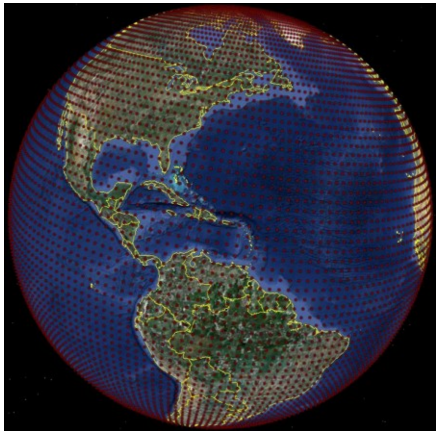
- Nearby Observations
- Wind Map
- Slope
- Deviation From Fitted Plane



Tools (Mid-Stage)

- NCAR / NCEP Global Reanalysis
  - WRF (dynamic downscaling)
  - Multivariate regression

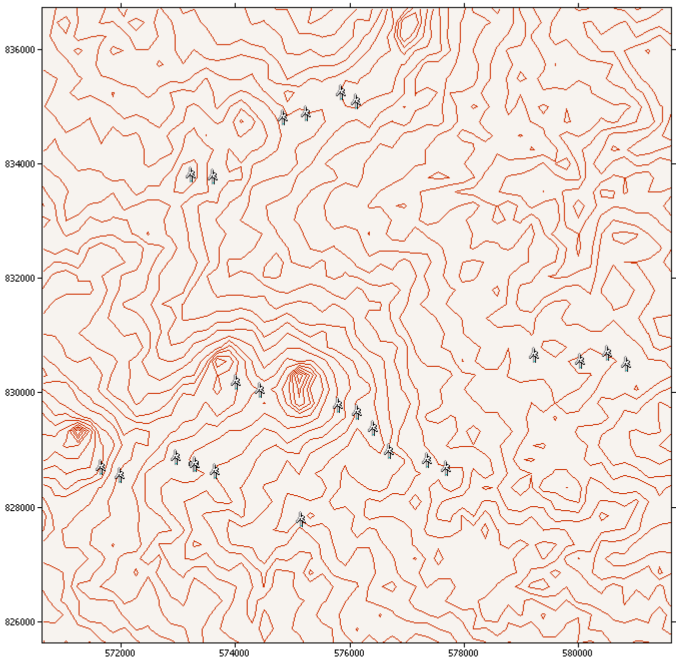




- On-site Observations
  - MET towers (lots and lots of MET towers!)
  - Sodar & Lidar
    - Captures scales relevant to terrain and turbines

Tools (Mid-Stage)

- Spatial Modeling
  - WAsP (Jackson & Hunt Flow Model, 1975)
    - 2D Navier–Stokes equations
    - Assumes log velocity profile
    - Polar grid
    - Quick
    - Validated for numerous types of terrain
      - Including terrain where it shouldn't be applied
    - Black box
  - Windfarmer
    - Used to calculate turbine wake impacts & energy yield
    - Includes eddy viscosity wake model
    - Can be initialized from many flow models



Tools (Late Stage)

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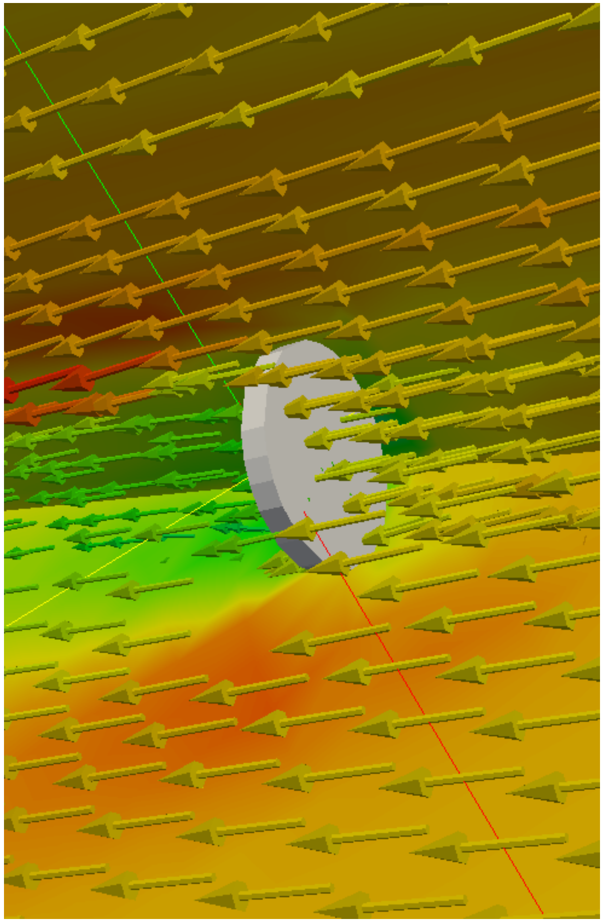
- OpenFOAM (CFD)
  - FOAM (F)ield (O)perations (A)nd (M)anipulation library
  - OpenFOAM is an Open Source C++ library and collection of solvers (executables)
  - OpenFOAM is particularly well suited for interface tracking problems (i.e. two or more fluids).
  - OpenFOAM is not specifically designed for atmospheric flows like WRF but is easily modified by comparison.

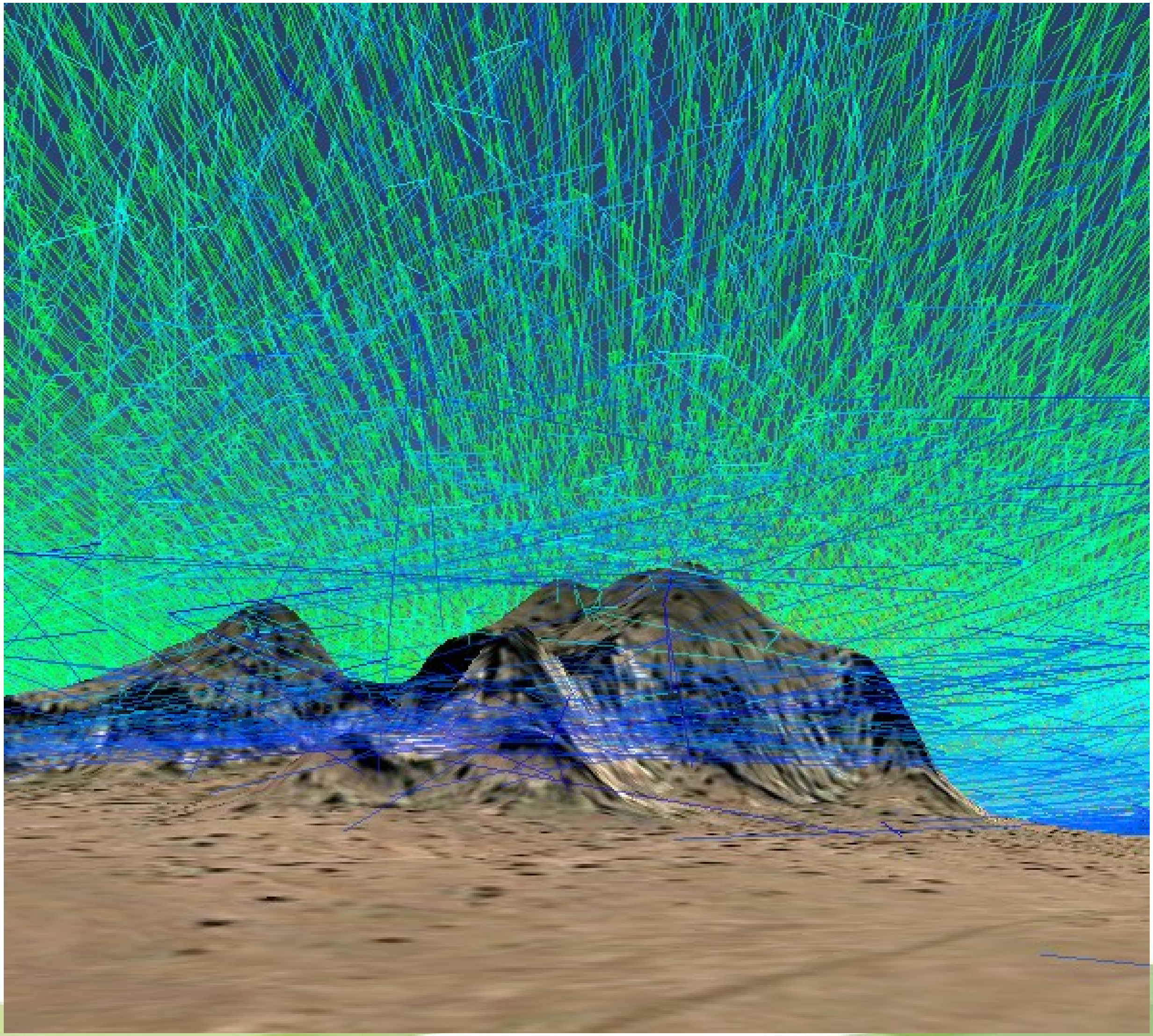


Tools (Late Stage)

- OpenFOAM Solver
  - **buoyantPimpleFoam** - Transient solver for buoyant, turbulent flow of compressible fluids
    - Includes the gravitational body force
  - **buoyantBoussinesqPimpleFoam** - Transient solver for buoyant, turbulent flow of incompressible fluids
    - Includes the gravitational body force
    - Uses Boussinesq approximation
  - **simpleWindFoam** – Steady-state solver for incompressible, turbulent flow
    - Does not include the gravitational body force
    - Includes external source in the momentum equation to approximate wind turbines

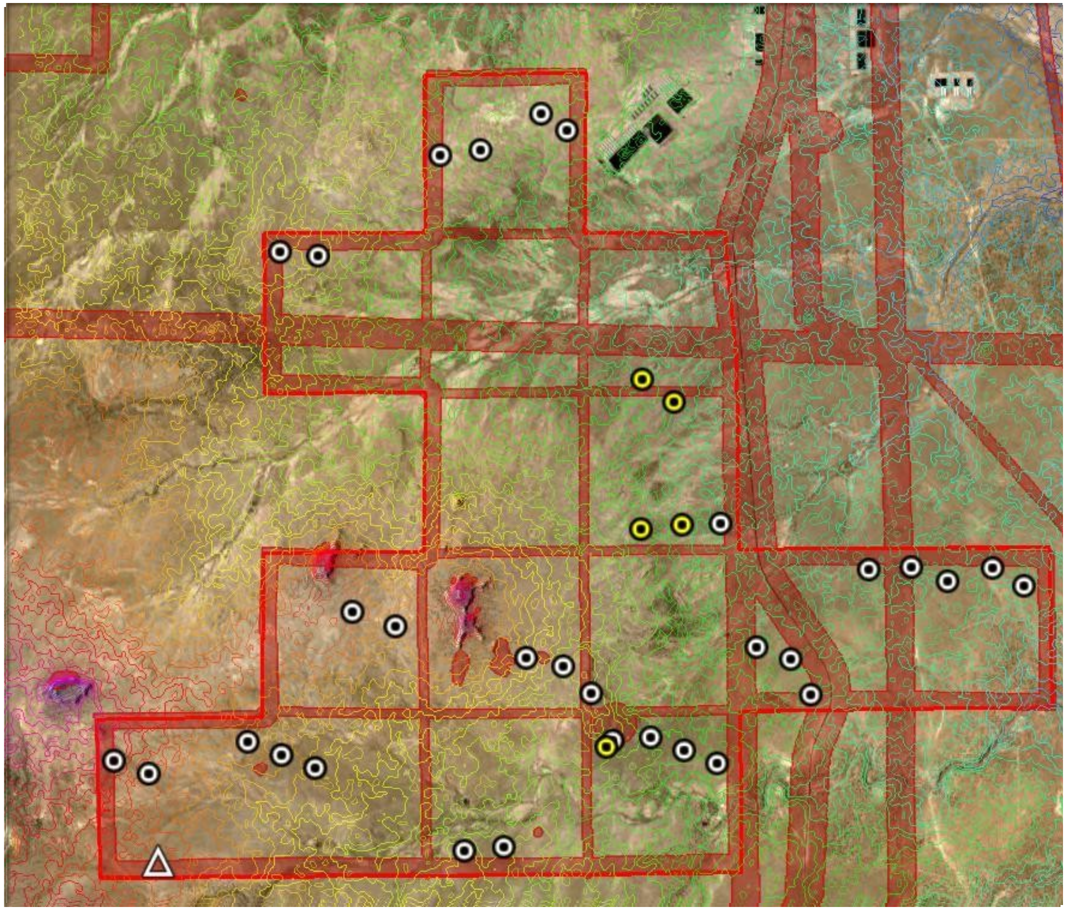
Tools (Late Stage)

- Wakes due to terrain are visible
- Complex flows can be visualized



Tools (Beginning to End)

- Application of tools to real example
  - Layout Revision
    - Setback analysis
    - Input from observational campaign
- As-Builts

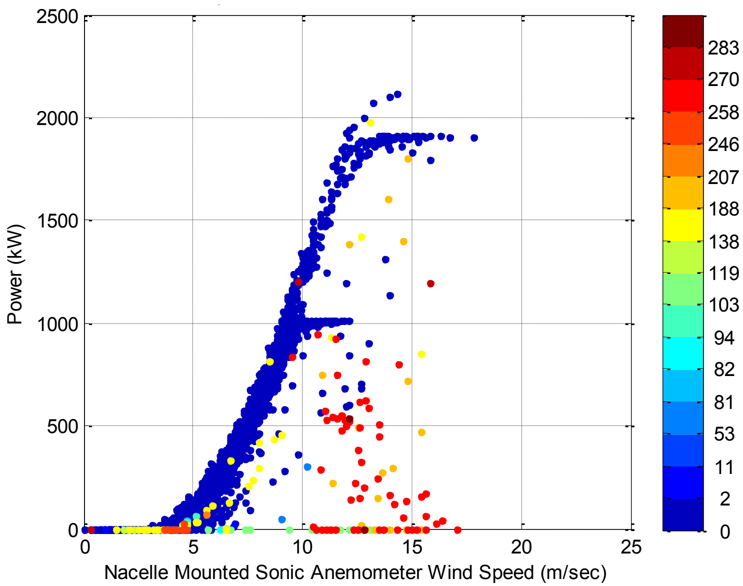


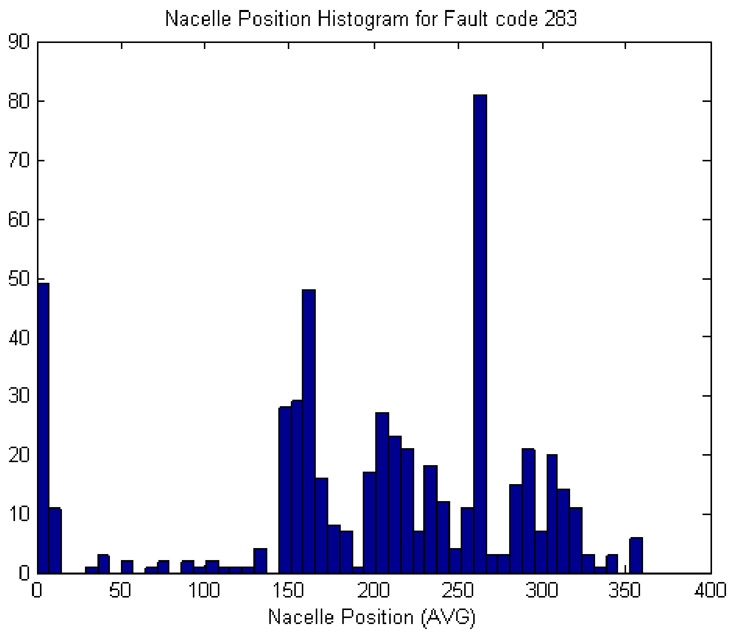
Tools (Operational)

- Retrospective Study (Monthly / Quarterly)
  - Permanent on-site meteorological facility
  - Past climate (Global reanalysis)
  - Helpful to have overlapping observation periods with development METs

Tools (Operational)

- Performance
  - Analysis of faulting
    - Is it based on turbine placement or something else?





  - Does faulting display a directional dependence?
    - Placement?

Summary

- Systems engineering enables one to optimally managing a technically complex system such as wind farm development and operations
- Numerous wind farm design tools are available to help the meteorologist with most tasks
- When wind farm development through operations is viewed as a whole, successive wind farms will have higher performance
- Application of these tools, plus continuous updating tools and methodology, will ultimately yield higher performing wind farms

Questions

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