# Wind Turbine Layout Optimization With Sequential DoE and Active Machine Learning

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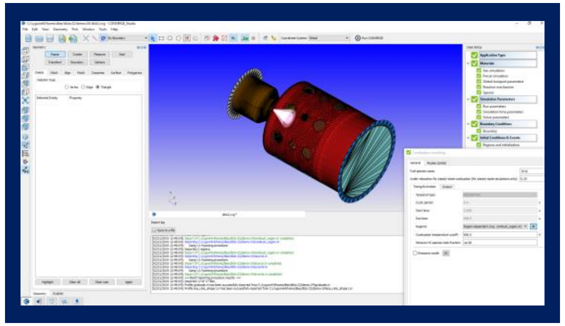
# What is CONVERGE?

## CONVERGE is an all-inclusive package for the CFD workflow

- CONVERGE Studio: Graphical user interface equipped with powerful geometry cleanup tools
- CONVERGE solver: Autonomous meshing and advanced physical models lead to highly accurate solutions
- Post-processing software: Integrated ParaView module and Tecplot for CONVERGE licenses included at no extra cost
- CONVERGE Horizon: Cloud computing platform that offers easy and affordable access to state-of-the-art hardware



*CONVERGE Studio*

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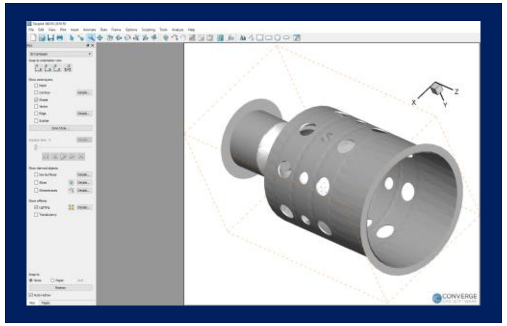


*Post-Processor*

HORIZON

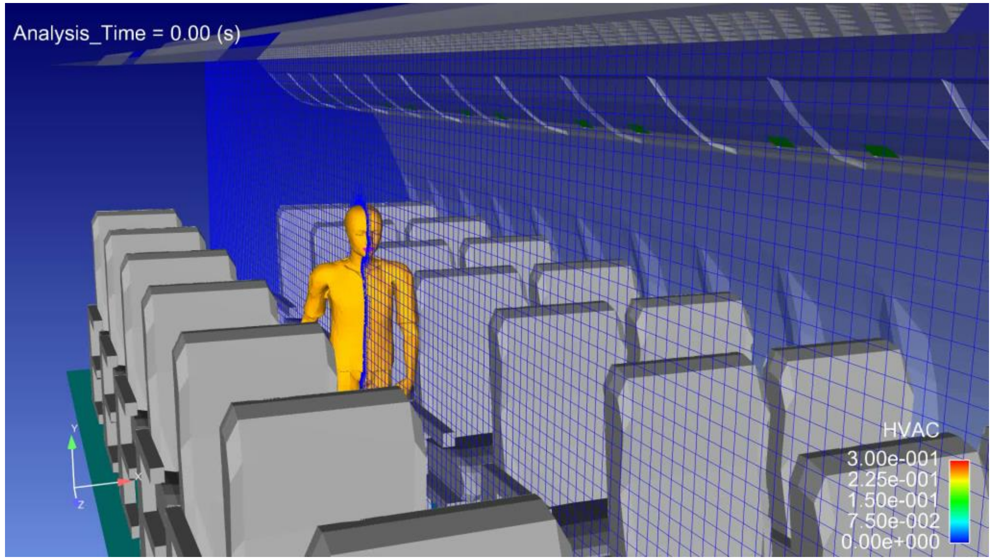
# Autonomous Meshing in CONVERGE

- Traditional CFD codes require the mesh to be created manually before simulation
  - Long meshing times
  - Meshing by guessing
    (areas needing refinement often change in time)
  - Low-quality mesh
  - Hard to determine grid convergence
    (if you change your mesh, does your answer change?)


- CONVERGE automatically generates the mesh at runtime
  - No user meshing time
  - Adaptive Mesh Refinement (AMR) = no more guessing
  - Orthogonal cells
  - Grid-convergent modeling

# Advanced Physical Modeling in CONVERGE

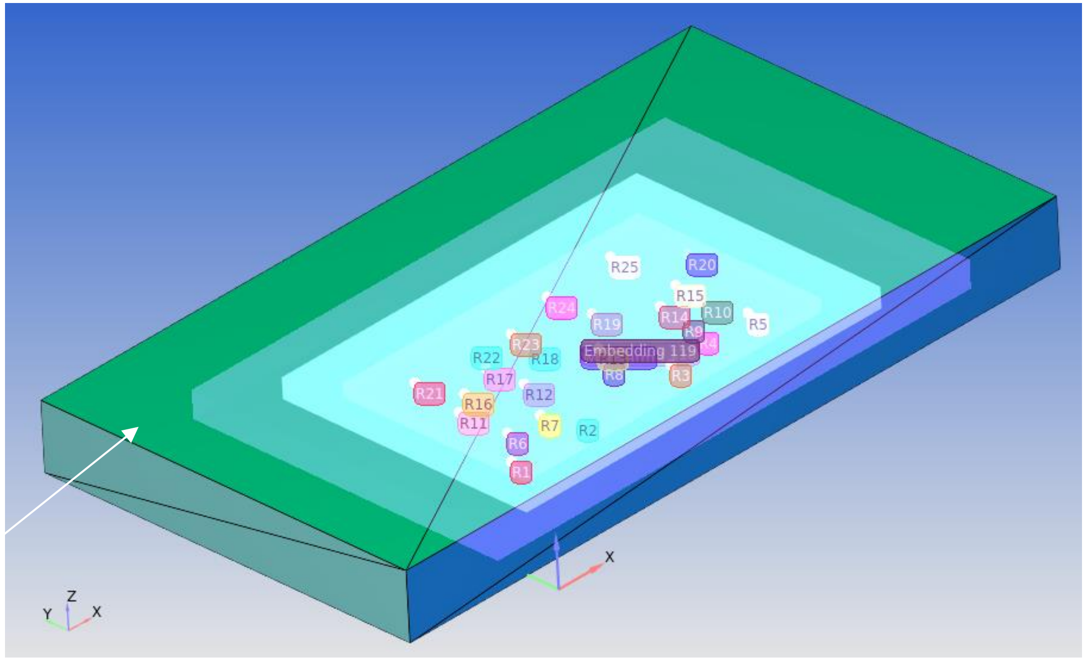
- Steady-state and transient solvers
- Fluid-structure interaction modeling
- Conjugate heat transfer modeling
- Multi-phase flow modeling
- Detailed chemistry solver
- Efficient combustion models
- State-of-the-art turbulence models
- Rich suite of chemistry tools
- Machine learning optimization




*Spray burner*

# Wind Farm Design

- Wind farm configurations
- 25 NREL 5*MW* wind turbines
- Land area: 4.8 *km* * 2.6 *km*
- Neutral atmospheric condition with constant wind speed and direction
- Optimize layout for maximum power production

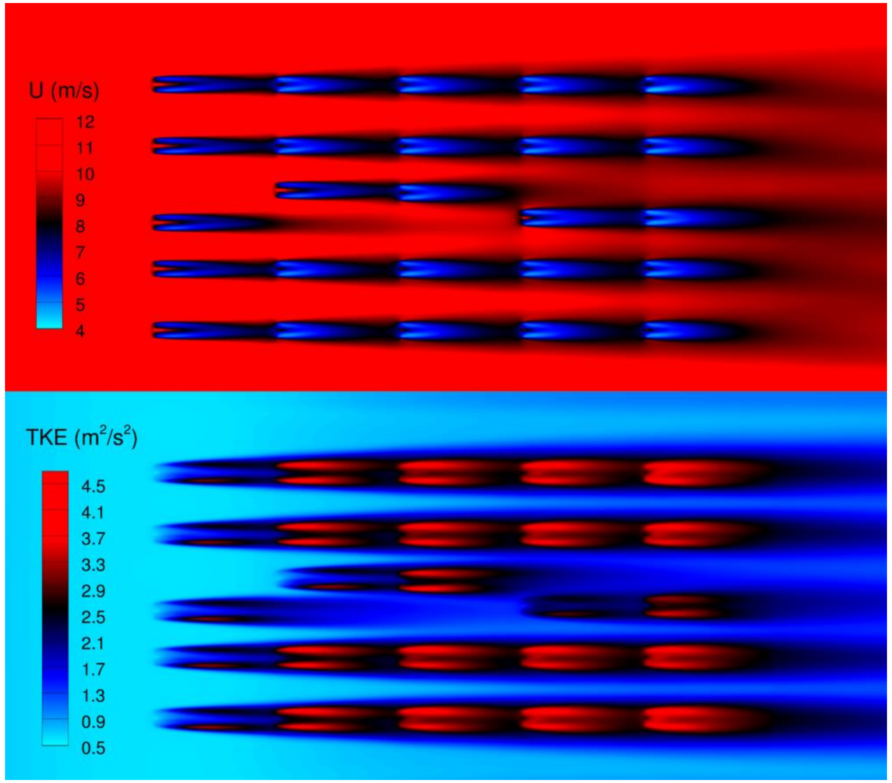



*Computational domain and wind turbine locations*

# Wind Farm CFD

- Wind farm model configuration:
  - Mean wind speed: 12 *m/s*
  - Turbulence intensity: 0.1
  - Domain size: 11 *km* * 6 *km* * 1 *km* in x, y, z
  - Grid size:
    - 256 *m* base grid
    - 4 *m* at rotor
    - 8 *m* in the wakes
  - Turbulence model: Reynolds Stress RANS model
  - Rotor model: RADM
  - Physical time: 1 hour
- For each wind farm CFD run:
  - Total cell count: 8 million
  - Wall time: 2.5 hour on 1 Horizon node (192 cores)

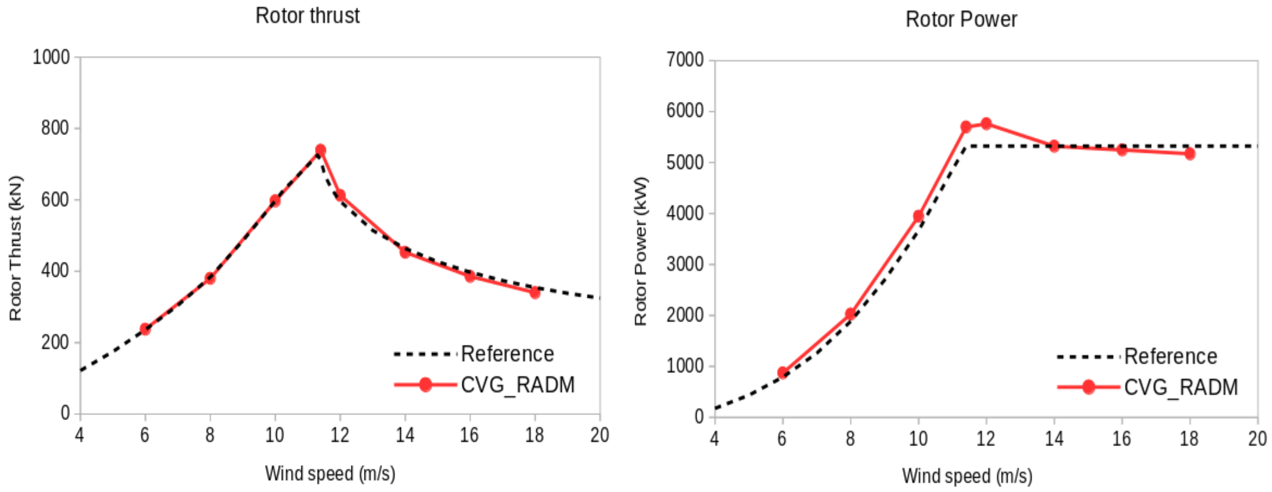
>50% loss due to wake effect



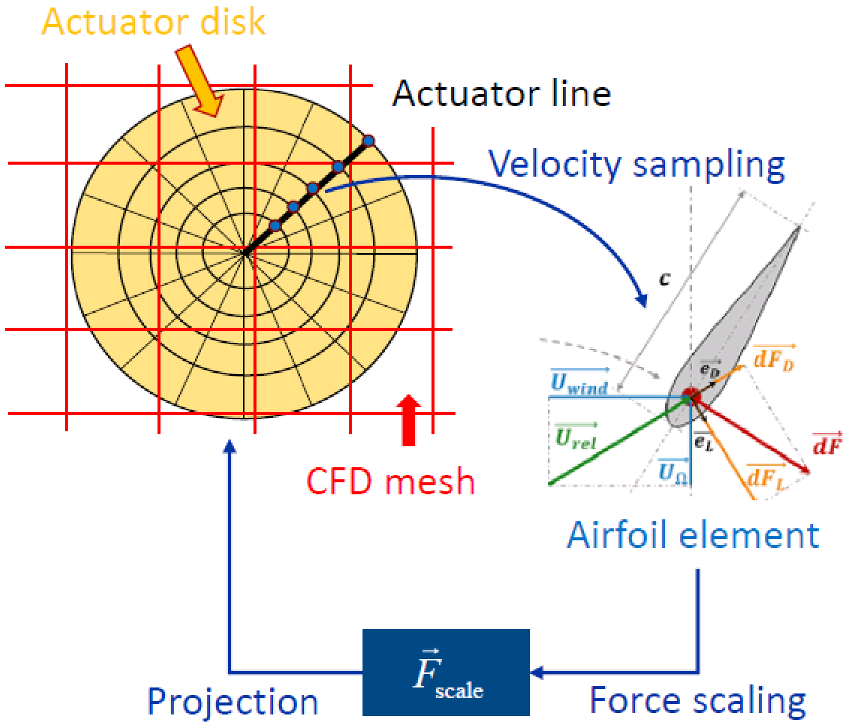

*Mean velocity and turbulence kinetic energy (TKE) fields in a wind farm CFD simulation*

# Rotational Actuator-Disk Model (RADM)

- Capture key aerodynamics of wind turbines without resolving turbine blades
- Much lower computational cost
- Very good scalability for HPC
- Very efficient simulation of large wind farms




*Validations of RADM simulating a standalone NREL 5MW wind turbine at various wind speeds*
*(The reference is from Jonkman et al, NREL/TP-500-38060, 2009)*




Schematic representation of the RADM

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# Rapid Optimization With Machine Learning

- Obtain training data with design of experiments (DoE)
  - Sequential batches
- Train & test machine learning emulator
  - Augment DoE if accuracy is unacceptable
- Run optimizer on emulator to obtain proposed optimum
- Obtain CFD result for proposed optimum

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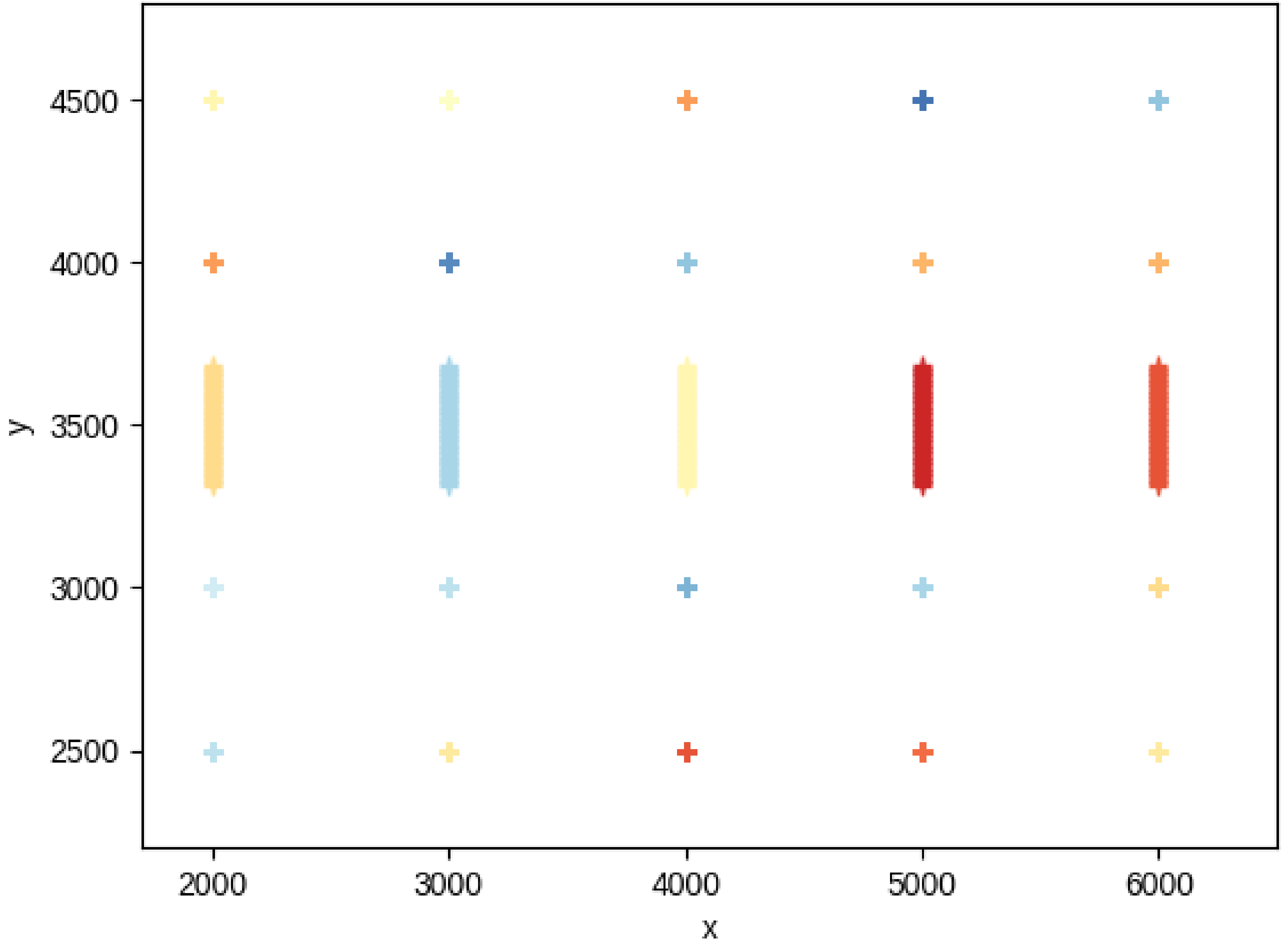
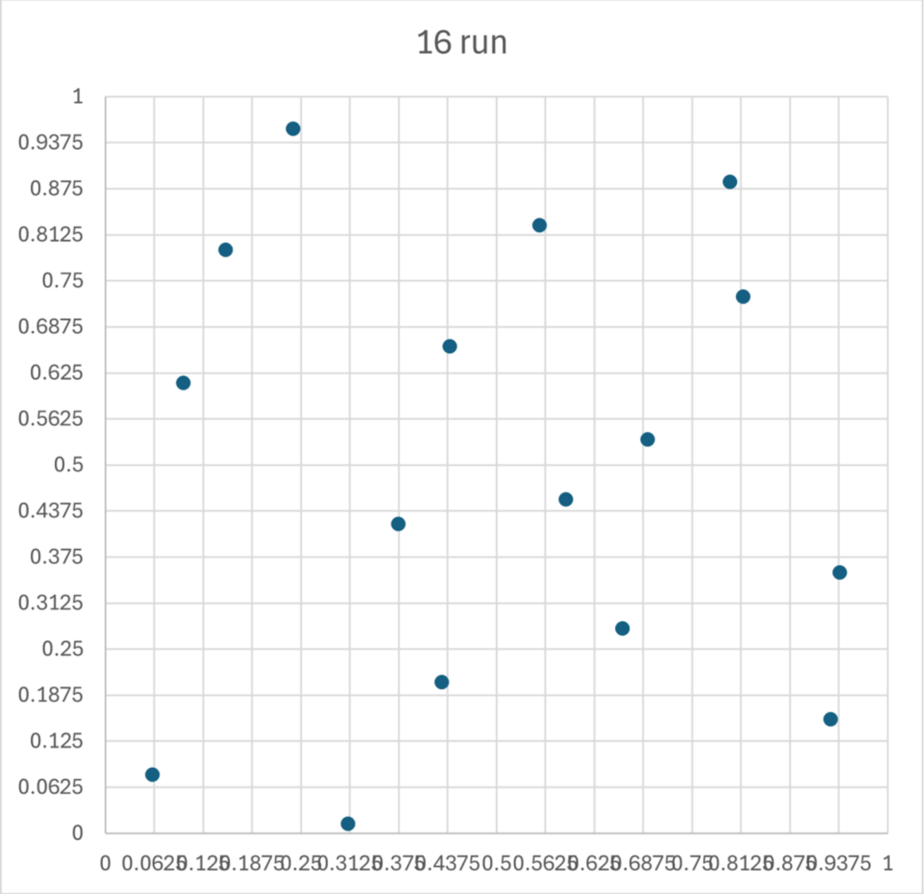
# Five Parameter Optimization for Max Power

- The y position of the center five wind turbines are allowed to vary +/- 187 *m*
- Total power of the wind farm (25 turbines)



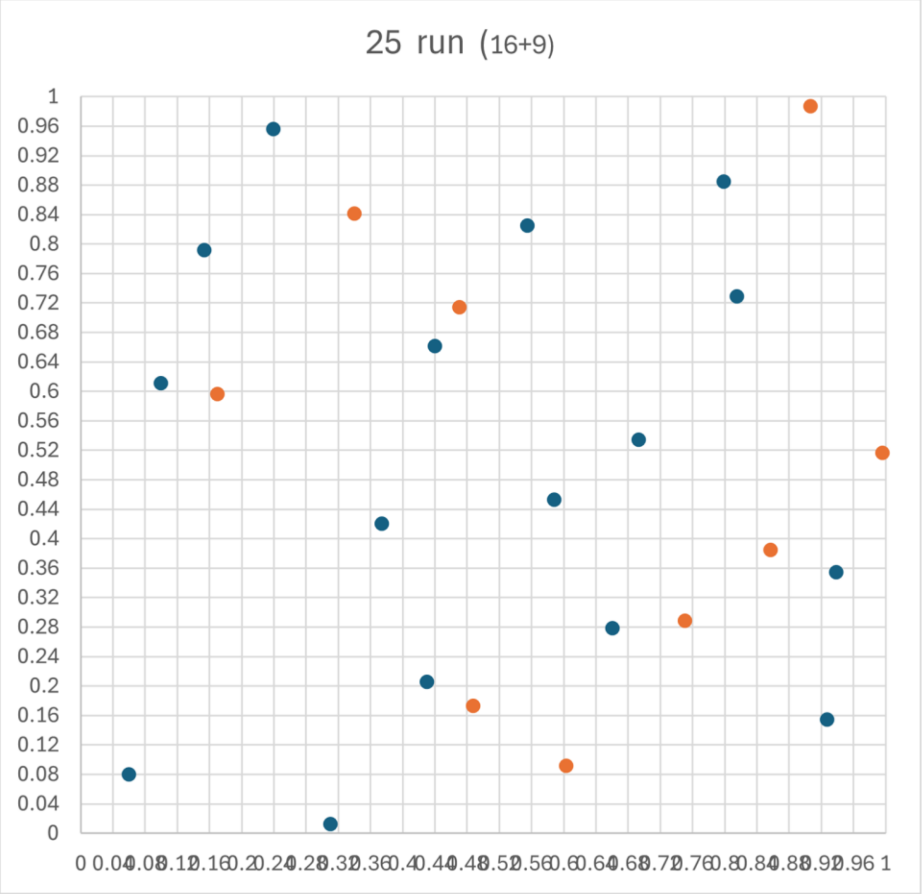
# DoE Definition

- Latin Hypercube Sampling (LHS)
  - User-defined number of runs
  - Random sampling within 'cube'
  - Iterate to maximize spacing between design points
    - Maximize the minimum Euclidean distance between design points



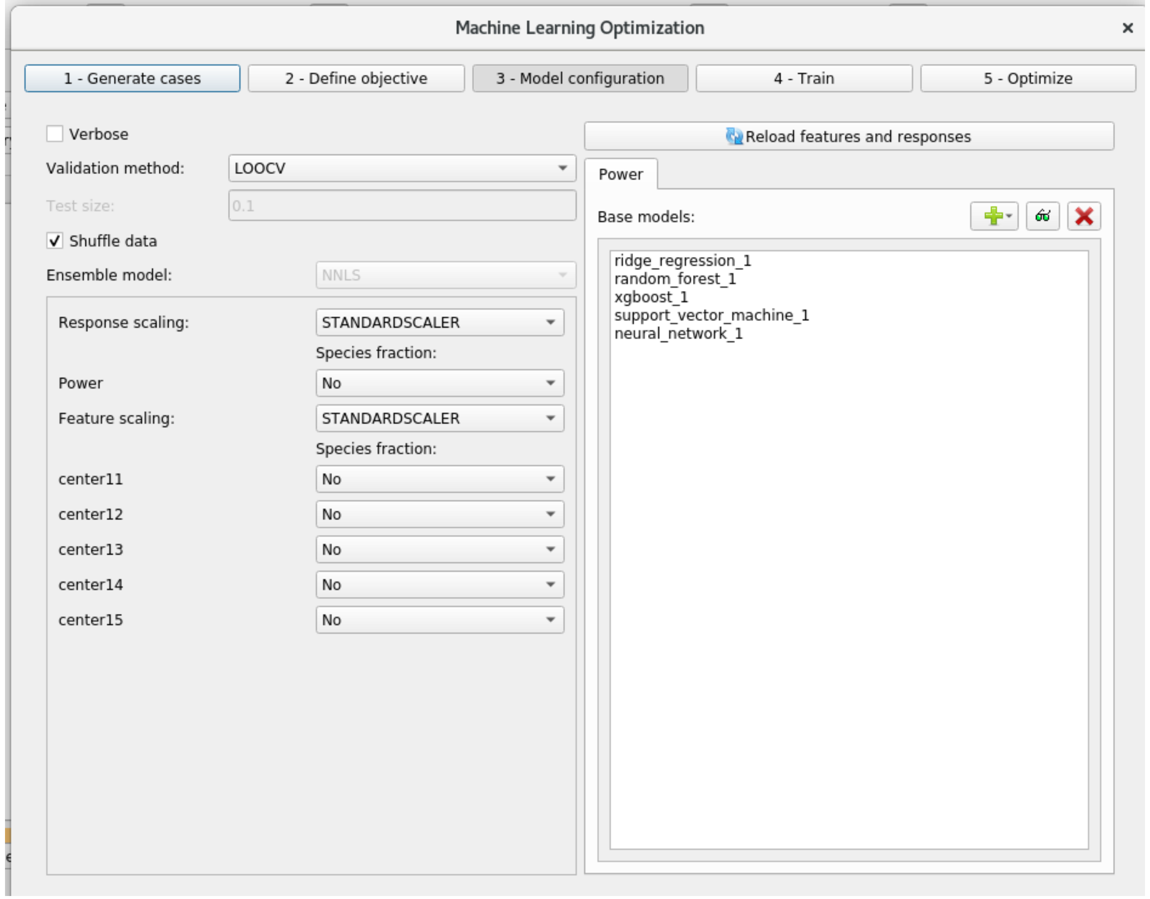
# DoE Definition

- Augment design
  - Increase the number of ‘cubes’
  - Find which cube each original DoE point belongs to
  - Place new designs in unoccupied cubes to create a valid DoE of total runs, iterate to maximize spacing
    - (Or as close to valid LHS as possible)



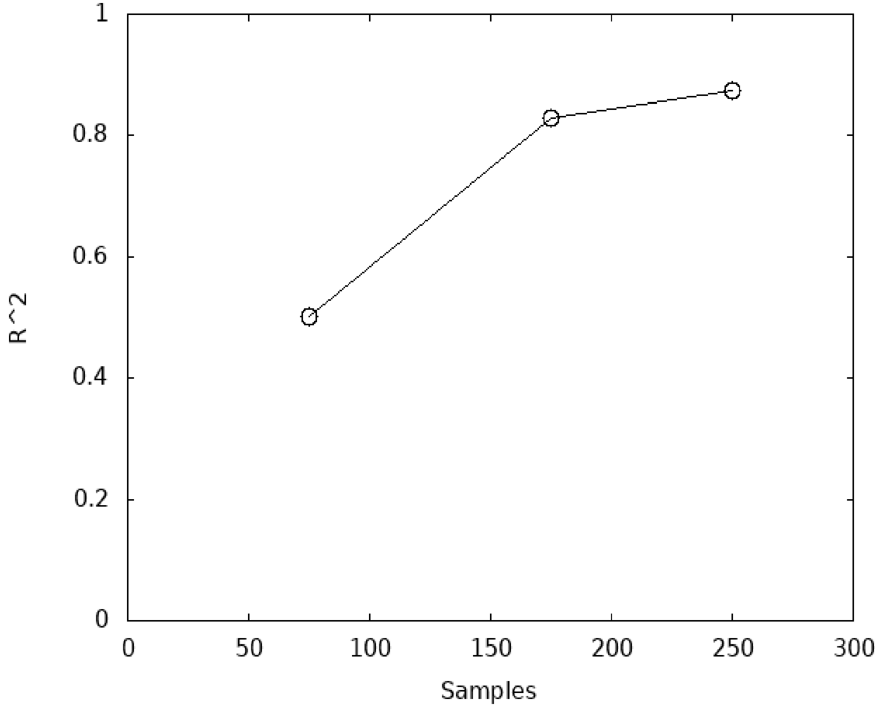
# Meta Learner ML Model

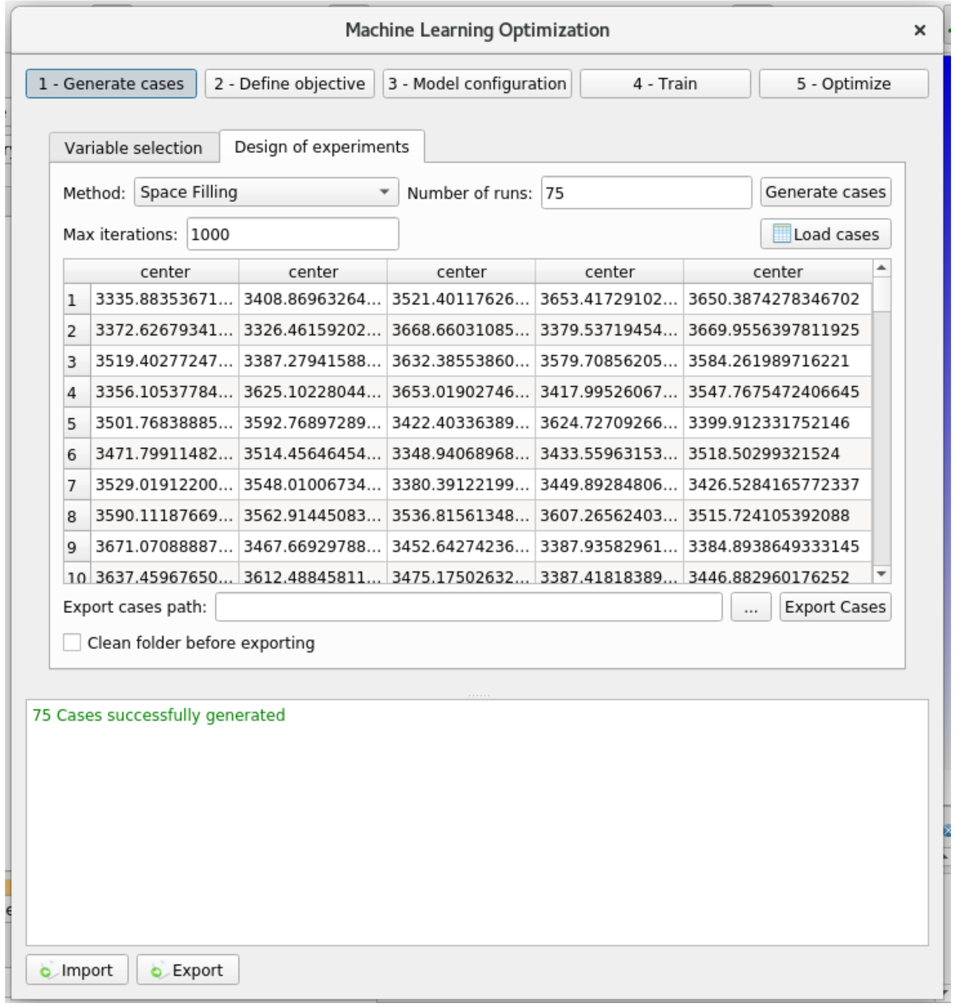
- 'Best' machine learning algorithm is unknown a priori
- Meta learner combines multiple ML strategies
  - Ridge Regression
    - alpha=0.0001
  - Random Forest
    - Depth 5, Trees 10
  - Gradient Boosting
    - Depth 5, Estimators 3000, learning rate 0.01
  - Support Vector Machine
    - Nu = 0.5, C = 16
  - Neural Network
    - 50 Neurons, 1 layer, Tanh activation, LBFGS optimizer
- Train/test method: "leave one out cross validation" (LOOCV)



# Train/Test Results

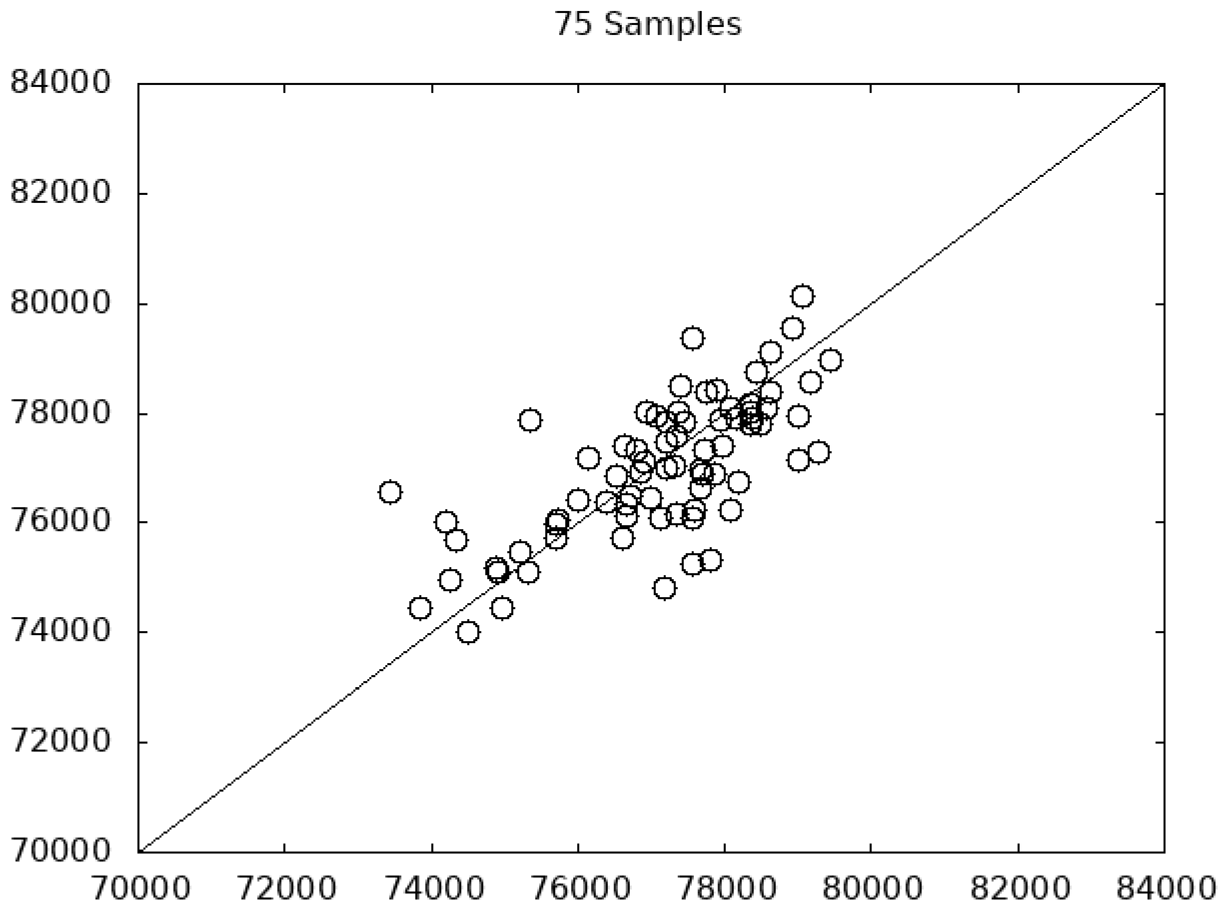
- DOE 75: $R^2 = 0.50$
- DOE 175: $R^2 = 0.83$
- DOE 275: $R^2 = 0.87$



# Train/Test Results, 75 Samples

- LOOCV test result
  - $R^2 = 0.50$
  - RMSE = 0.74



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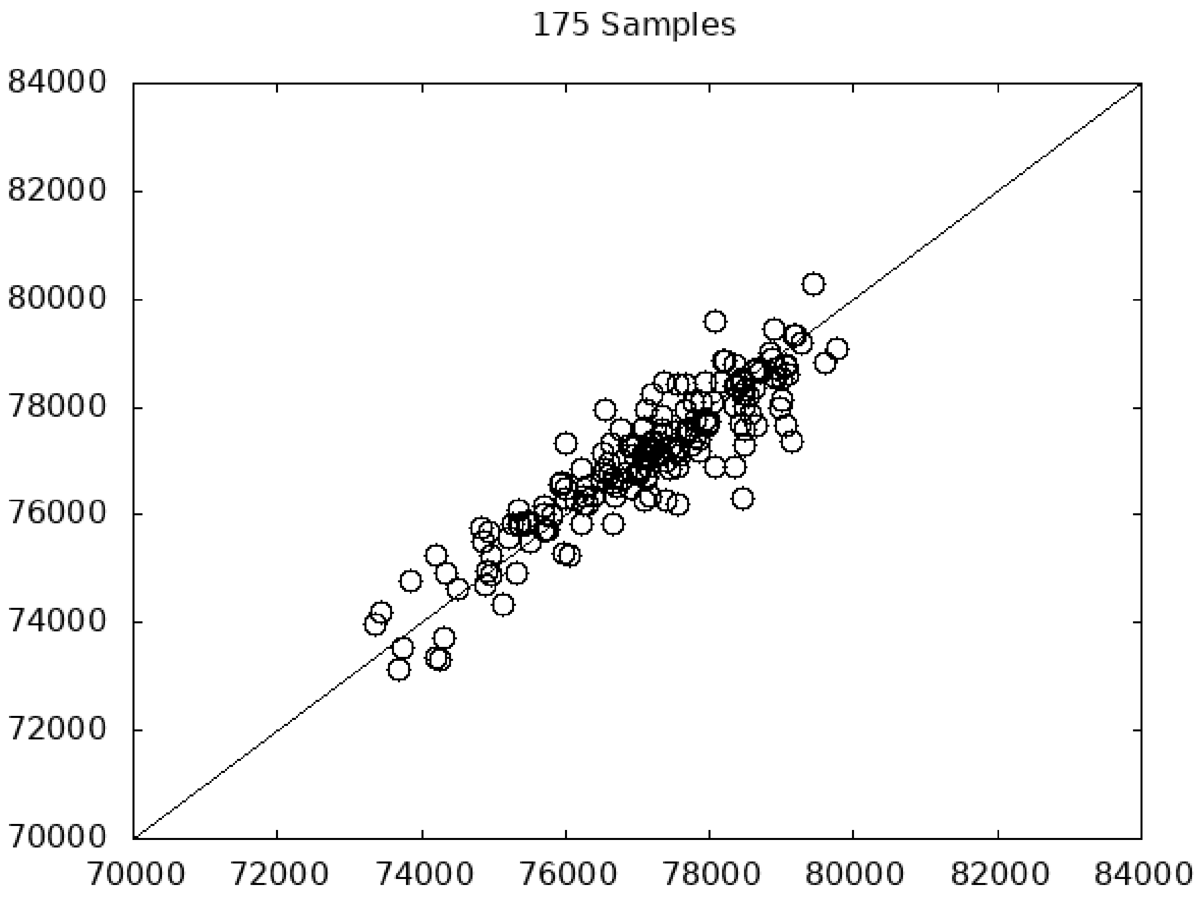
# Train/Test Results, 175 Samples

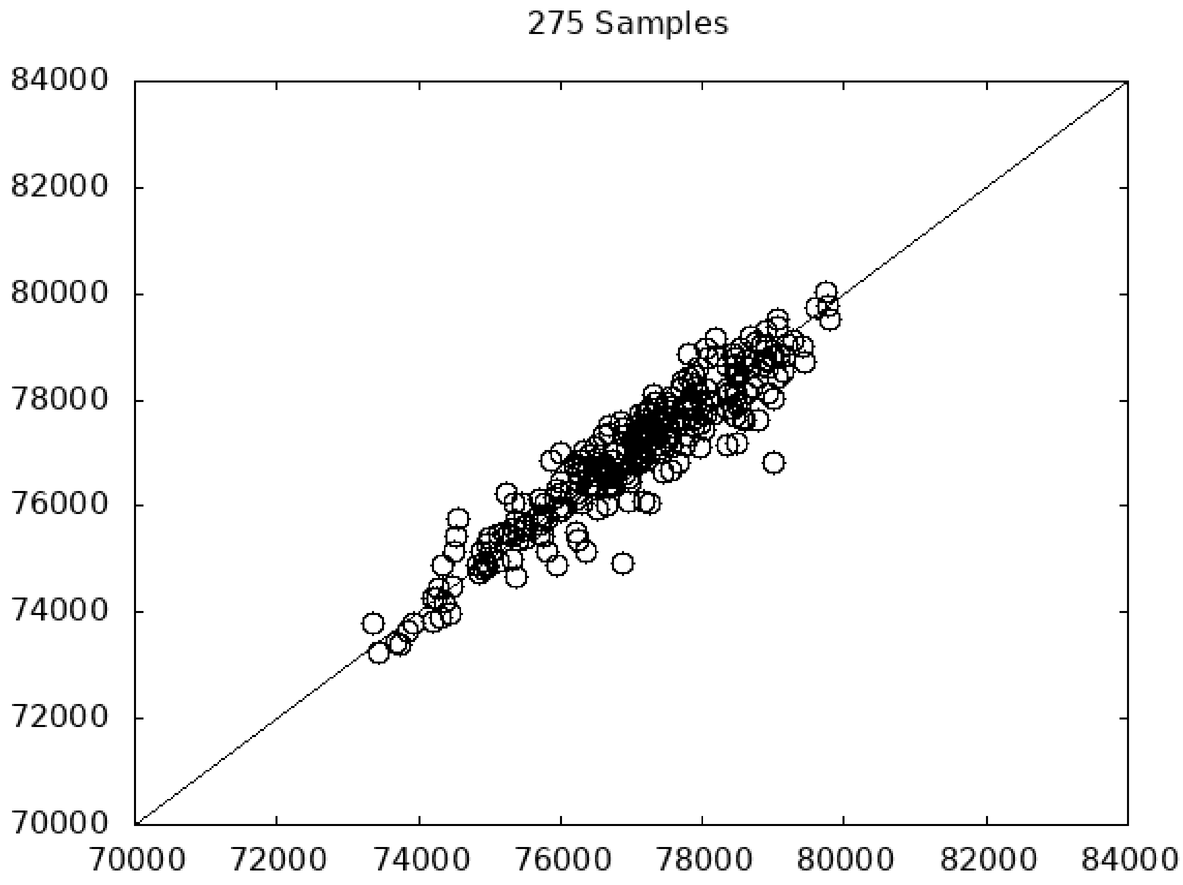
- LOOCV test result
  - $R^2 = 0.83$
  - RMSE = 0.42



# Train/Test Results, 275 Samples

- LOOCV test result
  - R^2 = 0.87
  - RMSE = 0.36

- If results have noise or variability, the upper limit on accuracy will be less than 1



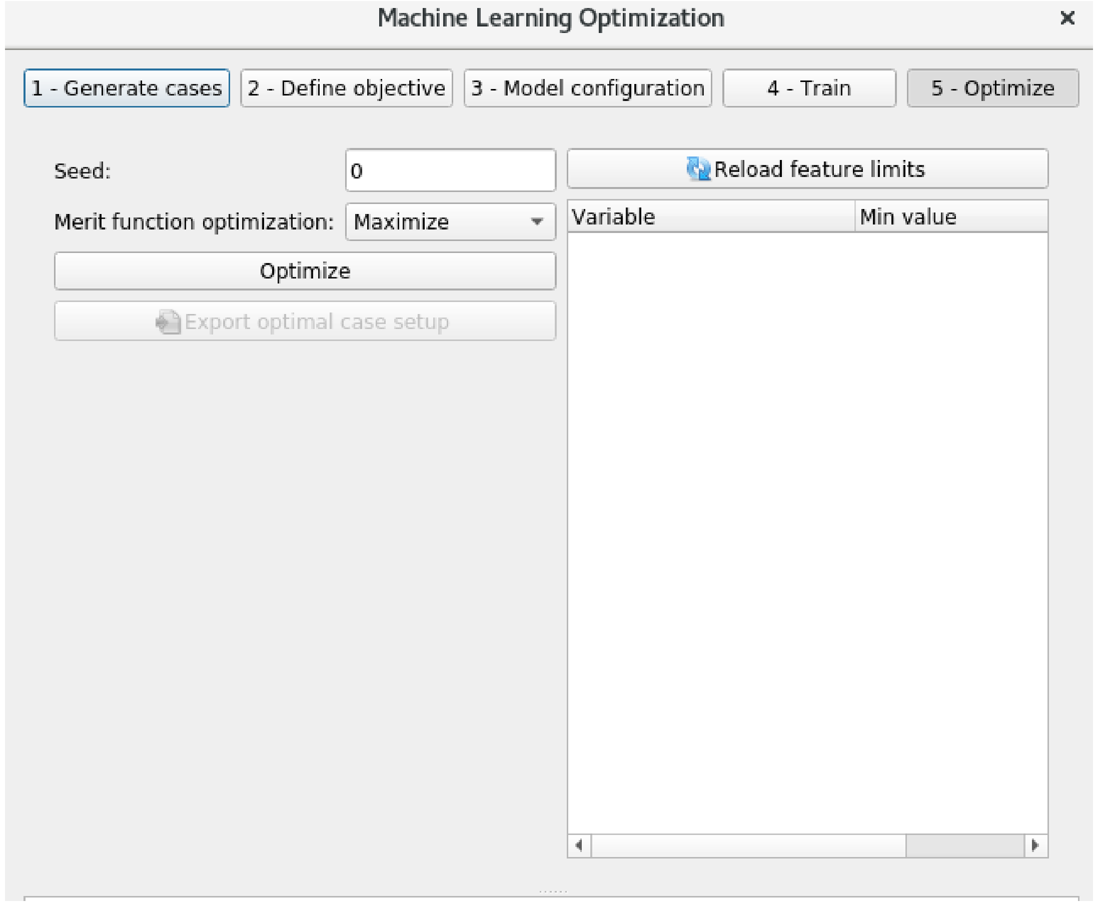
# ML Model, 275 Runs

- 1 minute to train
- Each execution of trained model takes 0.0005 secs

| Base_Model | CV_RMSE | Meta_Coeff |
|---|---|---|
| RidgeRegression_1 | 1.023179 | 0.000000 |
| RandomForest1 | 0.880304 | 0.000000 |
| XGBoost1 | 0.548271 | 0.070177 |
| NuSVR1 | 0.359740 | 0.112523 |
| NeuralNet1 | 0.176372 | 0.837697 |
| MetaRMSE | 1.651313e-01 | 1.000000 |

# Optimization

- The ML emulator was optimized by the DIRECT algorithm
  - NLOPT library, global optimizer
    - Optimization 2.5 secs, 5000 evaluations
- The ML optimization 'proposed' optimum to be confirmed with CFD-predicted power



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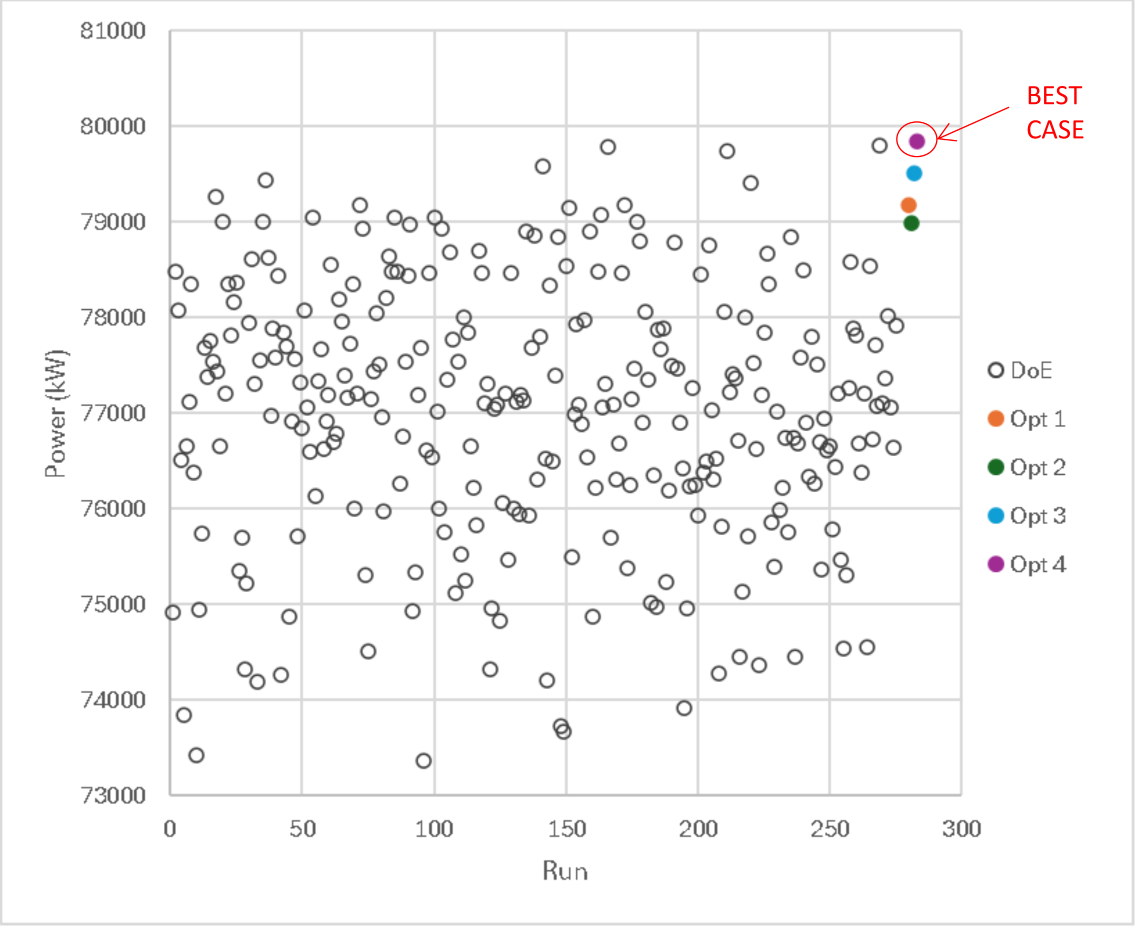
# Active Learning Optimization

- The ML emulator was optimized to obtain a 'proposed' optimum that was run in CFD to obtain the power
- Four successive optimums were obtained until 'best' power case achieved
- Added to the training dataset to update the ML emulator



# Optimum

Best case:

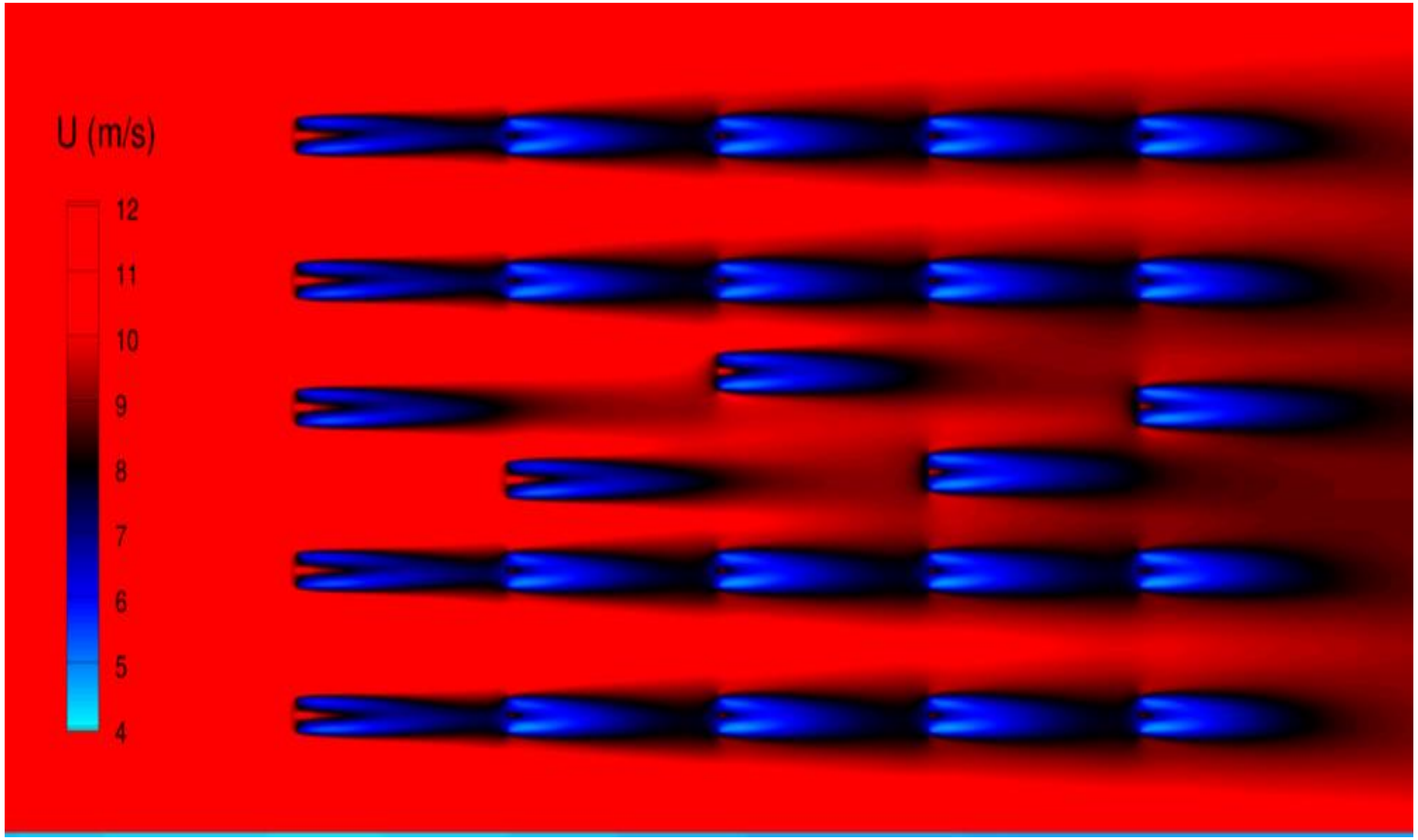
R11: 5354.52 *kW*

R12: 5144.49 *kW*

R13: 4121.79 *kW*

R14: 3209.89 *kW*

R15: 3183.21 *kW*



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# Conclusions

- DoE ML optimization method
  - Obtain DoE data in sequential batches until ML accuracy is achieved
    - Cost-effective method
    - DoE size unknown a priori (function of parameters and complexity of design space)
  - Optimize multiple times to enhance local accuracy near optimum: active learning

- Found an optimum wind farm layout for power production

# THANK YOU!

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