Wind Turbine Layout Optimization With Sequential DoE and Active Machine Learning

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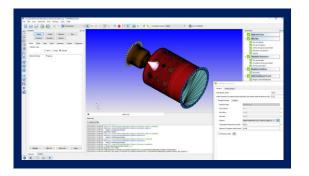




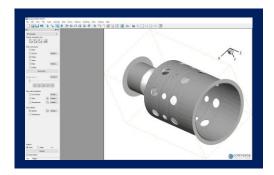
What is CONVERGE?

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



CFD SOFTWARE



HORIZON

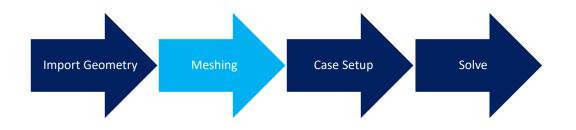
CONVERGE Studio

Post-Processor



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



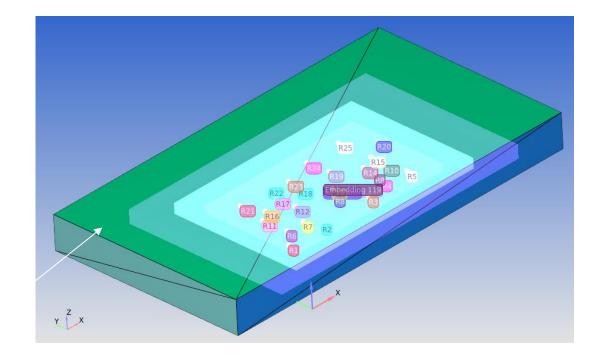


Spray burner



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



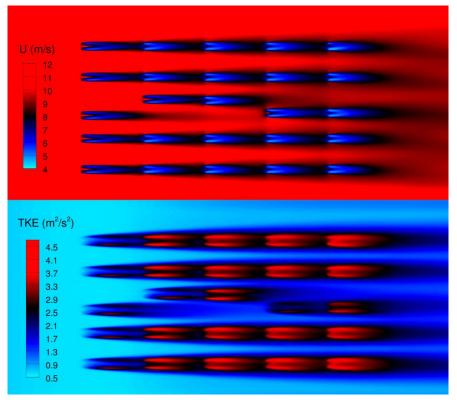
Computational domain and wind turbine locations



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

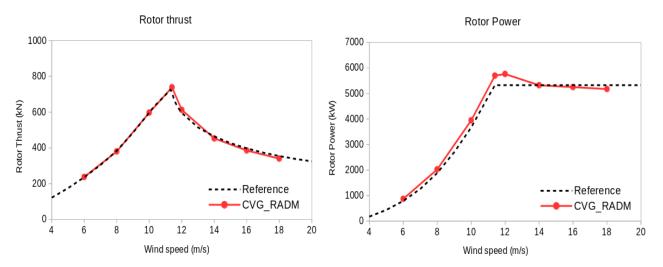


Mean velocity and turbulence kinetic energy (TKE) fields in a wind farm CFD simulation

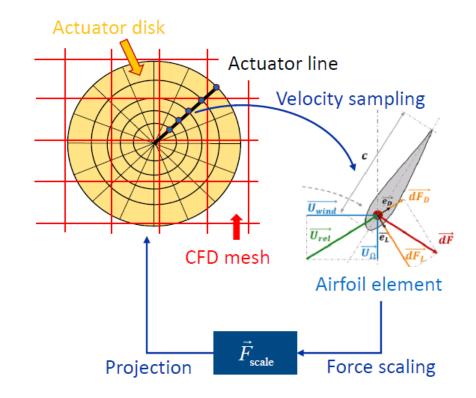


Rotational Actuator-Disk Model (RADM)

- 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



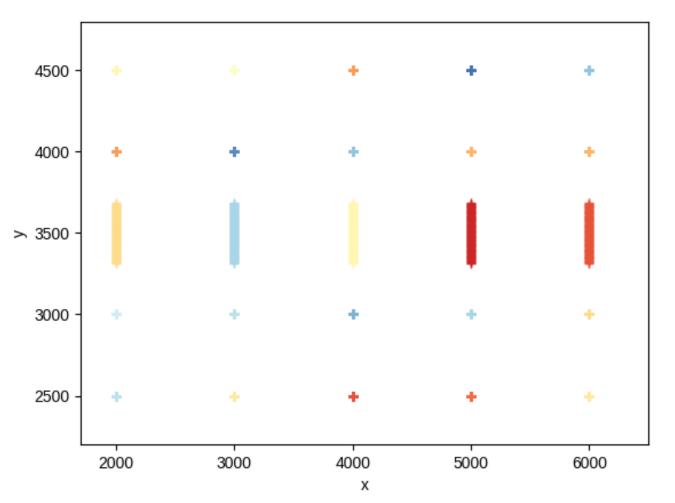
Rapid Optimization With Machine Learning

- 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



Five Parameter Optimization for Max Power

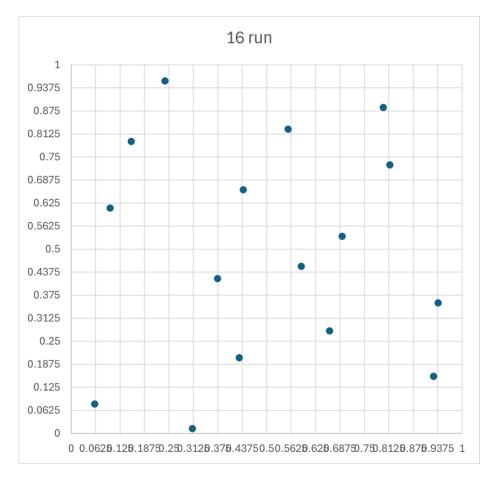
- The y position of the center five wind turbines are allowed to vary +/- 187 m
- Total power of the wind farm (25 turbines)





DoE Definition

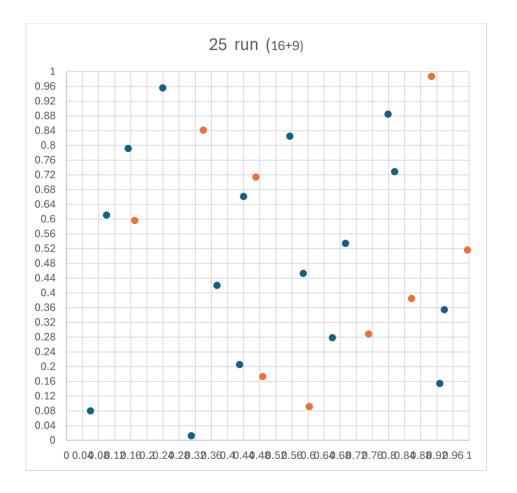
- Latin Hypercube Sampling (LHS)
 - User-defined number of runs
 - Random sampling within 'cube'
 - Iterate to maximize spacing between design points
 - Maximize the minimum Euclidean distance between design points





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

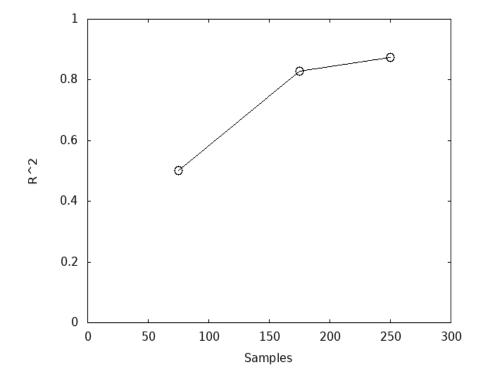
- 'Best' machine learning algorithm is unknown a priori
- Meta learner combines multiple ML strategies
 - Ridge Regression
 - alpha=0.0001
 - Random Forest
 - Depth 5, Trees 10
 - Gradient Boosting
 - Depth 5, Estimators 3000, learning rate 0.01
 - Support Vector Machine
 - Nu = 0.5, C = 16
 - Neural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

	2 - Define objective	3 - Model co	onfiguration	4 - Train	5 - Optimize
Verbose				Reload features and	responses
alidation method:	LOOCV	•	Power		
est size:	0.1		Base models:		
/ Shuffle data					
nsemble model:	NNLS	~	ridge_regressi random_forest	on_1 t_1	
Response scaling:	STANDARDSCALER		xgboost_1 support_vecto neural networ	r_machine_1	
	Species fraction:		neural_networ	K_1	
Power	No	•			
Feature scaling:	STANDARDSCALER	•			
	Species fraction:				
center11	No	•			
center12	No	•			
center13	No	•			
center14	No	•			
center15	No	•			



Train/Test Results

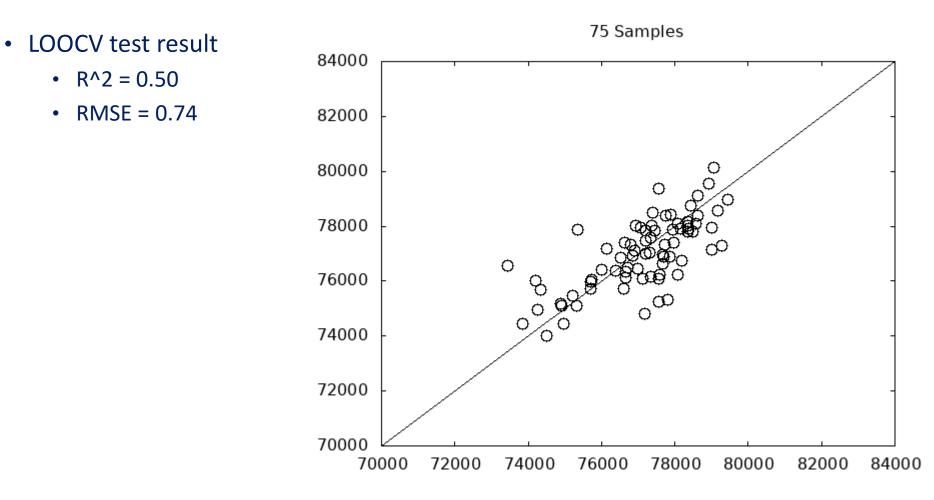
- DOE 75: R² = 0.50
- DOE 175: R² = 0.83
- DOE 275: R² = 0.87



aı	riable selection	Design of experime	ents			
let	thod: Space Filling		Number of runs:	75	Generate c	ases
a	x iterations: 1000				Load ca	ses
	center	center	center	center	center	
	3335.88353671	3408.86963264	3521.40117626	3653.41729102	3650.387427834670	2
	3372.62679341	3326.46159202	3668.66031085	3379.53719454	3669.955639781192	5
;	3519.40277247	3387.27941588	3632.38553860	3579.70856205	3584.261989716221	
Ļ	3356.10537784	3625.10228044	3653.01902746	3417.99526067	3547.767547240664	5
,	3501.76838885	3592.76897289	3422.40336389	3624.72709266	3399.912331752146	
;	3471.79911482	3514.45646454	3348.94068968	3433.55963153	3518.50299321524	
	3529.01912200	3548.01006734	3380.39122199	3449.89284806	3426.528416577233	7
;	3590.11187669	3562.91445083	3536.81561348	3607.26562403	3515.724105392088	
)	3671.07088887	3467.66929788	3452.64274236	3387.93582961	3384.893864933314	5
0	3637.45967650	3612.48845811	3475.17502632	3387.41818389	3446.882960176252	-
хþ	oort cases path:				Export C	ases
	Clean folder before	exporting				
_						
	es successfully gen	erated				
	es successionly gen	crated				

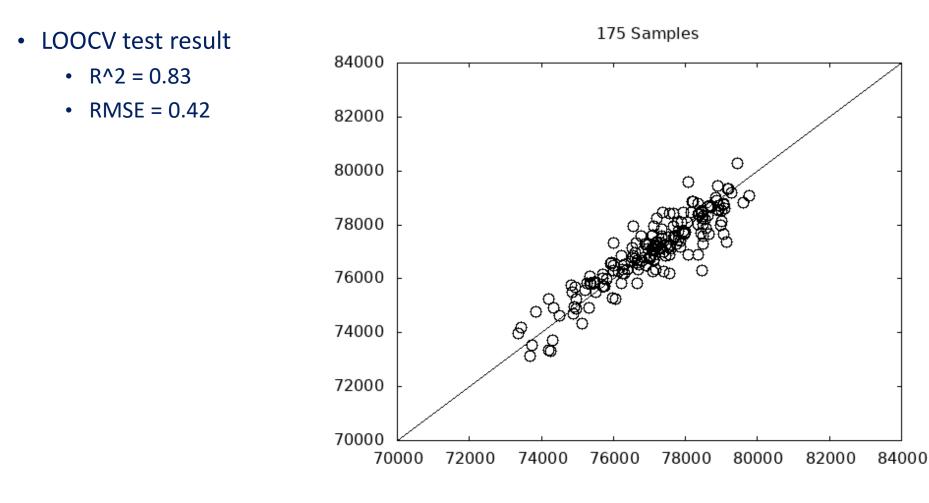


Train/Test Results, 75 Samples





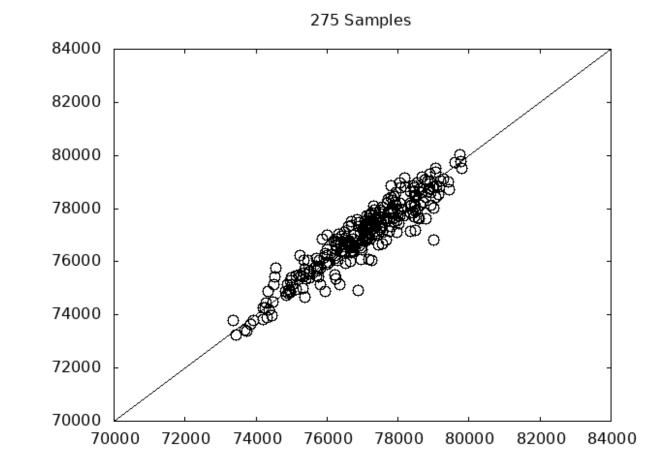
Train/Test Results, 175 Samples





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	0.00000
RandomForest1	0.880304	0.00000
XGBoost1	0.548271	0.070177
NuSVR1	0.359740	0.112523
NeuralNet1	0.176372	0.837697
MetaRMSE	1.651313e-01	1.000000



Optimization

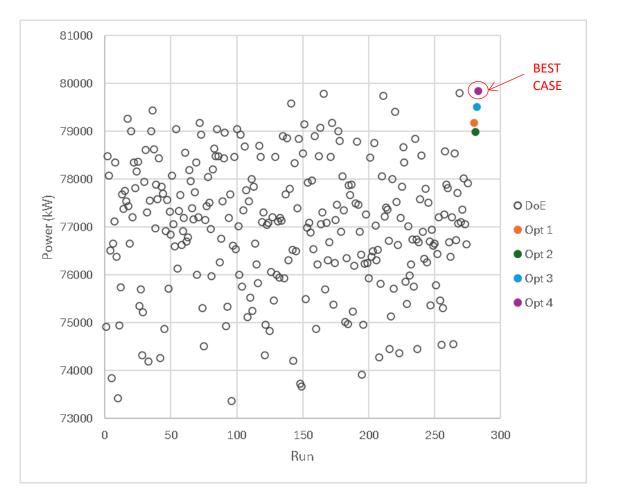
- The ML emulator was optimized by the DIRECT algorithm
 - NLOPT library, global optimizer
 - Optimization 2.5 secs, 5000 evaluations
- The ML optimization 'proposed' optimum to be confirmed with CFD-predicted power

	Machine Lear	ning Optimization	
- Generate cases 2 - Define	objective 3 - Me	odel configuration	4 - Train 5 - Optimize
Seed:	0	Reloa	d feature limits
Merit function optimization:	Maximize	▼ Variable	Min value
Optimize	2		
Export optimal of	case setup		
		4	•



Active Learning Optimization

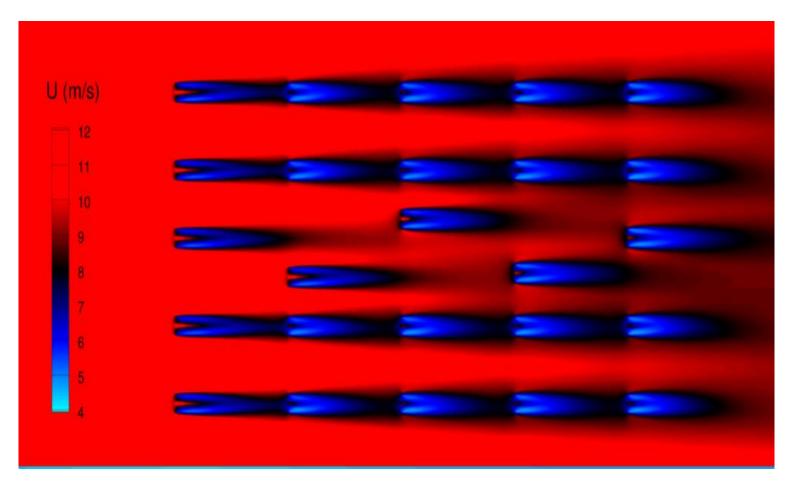
- The ML emulator was optimized to obtain a 'proposed' optimum that was run in CFD to obtain the power
- Four successive optimums were obtained until 'best' power case achieved
- Added to the training dataset to update the ML emulator





Optimum

Best case: R11: 5354.52 *kW* R12: 5144.49 *kW* R13: 4121.79 *kW* R14: 3209.89 *kW* R15: 3183.21 *kW*





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! CONVERGECFD.COM

