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ENGINEERING APPLICATIONS OF METAMODEL-BASED OPTIMIZATION: GENETIC ALGORITHMS COUPLED WITH ARTIFICIAL NEURAL NETWORKS

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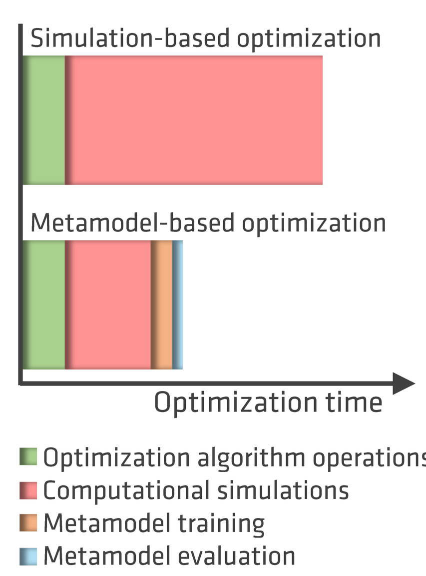
OPTIMIZATION IN ENGINEERING

The complexity of optimization problems in engineering leads to the necessity of developing methodologies to replace the usually time-costly computational models that simulation-based optimization requires. An alternative is to implement a metamodel (model of the model), for example artificial neural networks, to evaluate the objective function of the problem. This technique, called metamodel-based optimization, has become frequently used in recent years due to the fact that it can be implemented to solve large nonlinear problems, independently of the nature of the variables involved (continuous, discrete, binary, to name a few). Artificial neural networks (ANNs) are, regardless of being an approximate method, reliable and accurate models that can be implemented on several engineering problems.

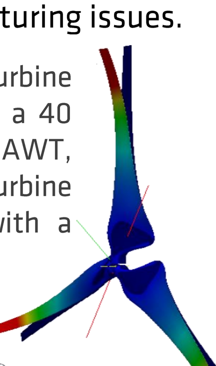


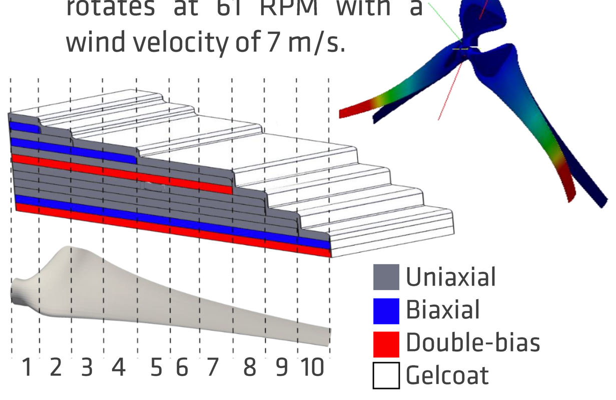
CASE STUDIES

1 COMPOSITE LAMINATED WIND TURBINE BLADES: MINIMIZATION OF WEIGHT [1]

Design problem: find the proper variable stiffness laminate that minimizes the weight of the blades while satisfying a series of design constraints that include mechanical and manufacturing issues.

6.70 m long wind turbine blade that belongs to a 40 kW three-blade HAWT, designed in [4] The turbine rotates at 61 RPM with a wind velocity of 7 m/s.

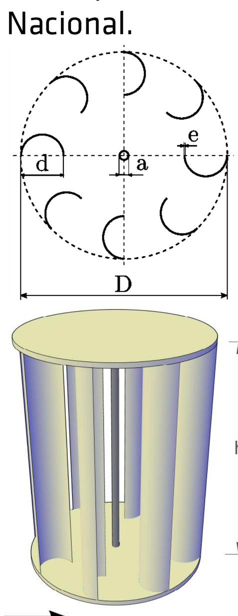




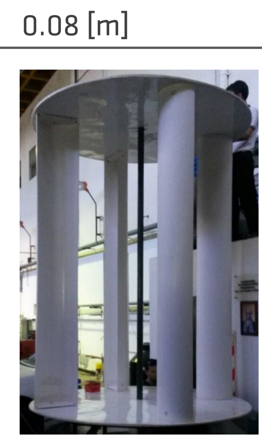
	Uniaxial	Biaxial	Double-bias	Gelcoat
E_x [GPa]	44	44	44	5
E_y [GPa]	12.6	44	44	5
G_{XY} [GPa]	10	35	15	1.8
Density [Kg/m^3]	1117	1004	914	650
Poisson ratio	0.32	0.36	0.36	0.4
Thickness [mm]	0.50	0.50	0.35	0.25

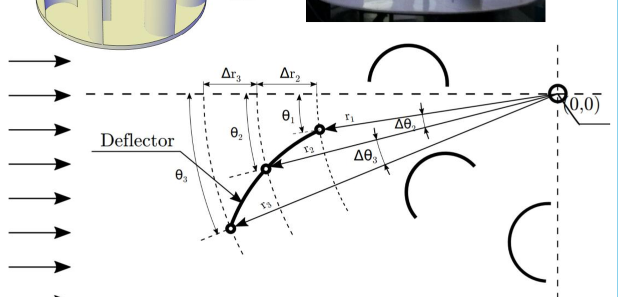
2 DEFLECTORS OF A WIND TURBINE (SAVONIUS): DESIGN AND OPTIMIZATION [2]

Design problem: find the optimal geometry and position of four fixed deflectors to improve the performance of an eight-blade Savonius vertical axis wind turbine (VAWT), which is being installed on the roof of the Santa Fe Regional Faculty of the Universidad Tecnológica Nacional.



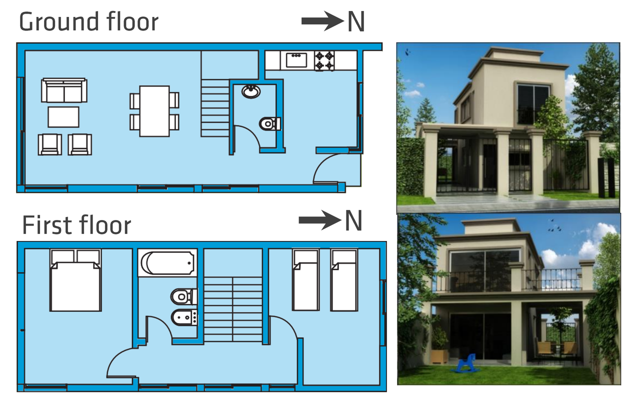
D	2.00 [m]	e	0.01 [m]
d	0.40 [m]	h	2.50 [m]
a	0.08 [m]		



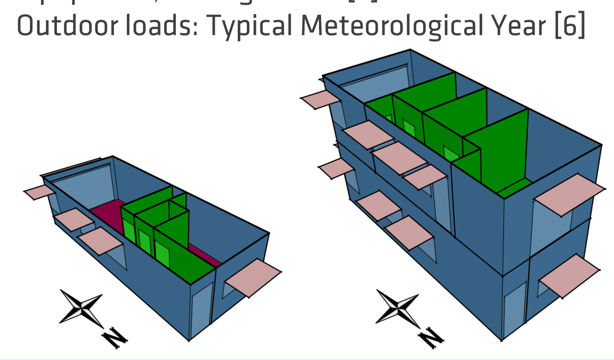


3 DWELLINGS: OPTIMIZATION OF ENERGY EFFICIENCY [3]

Design problem: improve the energy performance without affecting the thermal comfort of a single-family house, solving a multi-objective optimization problem.



Model: Roble 2D, funded by Pro.Cre.Ar. [4]
Total surface: 83 [m^2]
Location: Paraná, Entre Ríos, Argentina
Indoor loads: Lightning, occupants, electric equipment, among others [5]
Outdoor loads: Typical Meteorological Year [6]

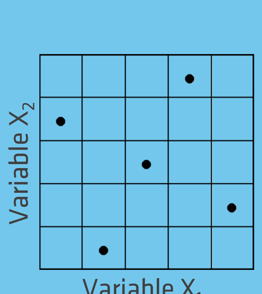


PROPOSED METHODOLOGY

SAMPLE VARIABLES

Latin Hypercube Sampling [7]

The range of each input variable is divided into N equally probable intervals, and a value from each interval is selected. Then, the selected values are matched randomly, creating a sample of size N.



	Training N	Validation N	Problem size
1	2000, 2500	100	~10^{14}
2	300	50	~10^{7}
3	1700, 3300	100	~10^{8}

SIMULATION

IFEM (Inverse Finite Element Method) [4,8,9] 1

It computes all of the design constraints: the maximum allowable tip deflection, the maximum stress criteria and the vibration frequency of the blades. It also determines the unloaded manufacturing shape of the blade such that, under service loads, the deformed blade attains its efficient aerodynamic shape.

CFD (Computational Fluid Dynamics) 2

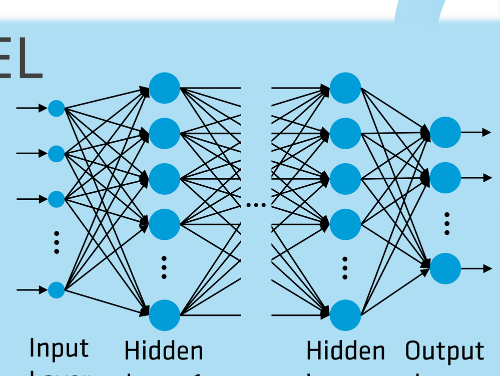
A two dimensional CFD model was employed to calculate the Power Coefficient (Cp), considering a wind velocity of 5 [m·s^{-1}] aligned with one cardinal direction and a Tip Speed Ratio (λ) of 0.4 [2].

EnergyPlus 3

EnergyPlus was used to evaluate the thermal and energy performance of the house. The house was divided into eight thermal zones (kitchen, living room, two bathrooms, two bedrooms, corridor, staircase), and was planned to be occupied by four people.

METAMODEL

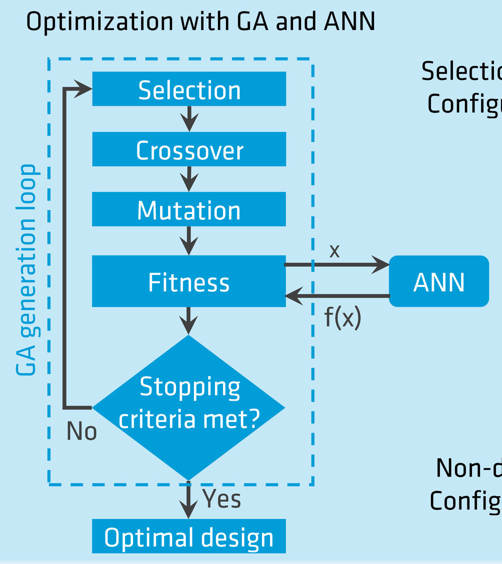
Multilayer Feedforward ANNs were developed for the three problems. Backpropagation with Bayesian regularization was implemented as training function, with an early stop criterion.



	N° of HL	Total N° of neurons	Performance Function
1	1 and 2	40 to 60	MSE=1x10^{-5}
2	1, 2 and 3	6 to 20 in each layer	MSE=1x10^{-7}
3	1, 2 and 3	0.5·(Input+Output) +(Sample Size)$^{1/2}$	MSE=1x10^{-5}

OPTIMIZATION

Optimization with GA and ANN



Genetic algorithm 1

Selection: Tournament, Crossover method: Laplace
Configuration: 48 individuals and 100 generations.
Total ANN evaluations: 4800

Genetic algorithm 2

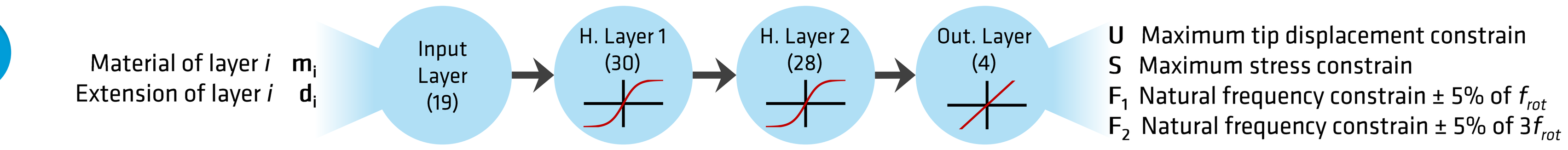
Selection: Tournament
Crossover method: Laplace
Configuration: 48 individuals and 100 generations. Total ANN evaluations: 4848

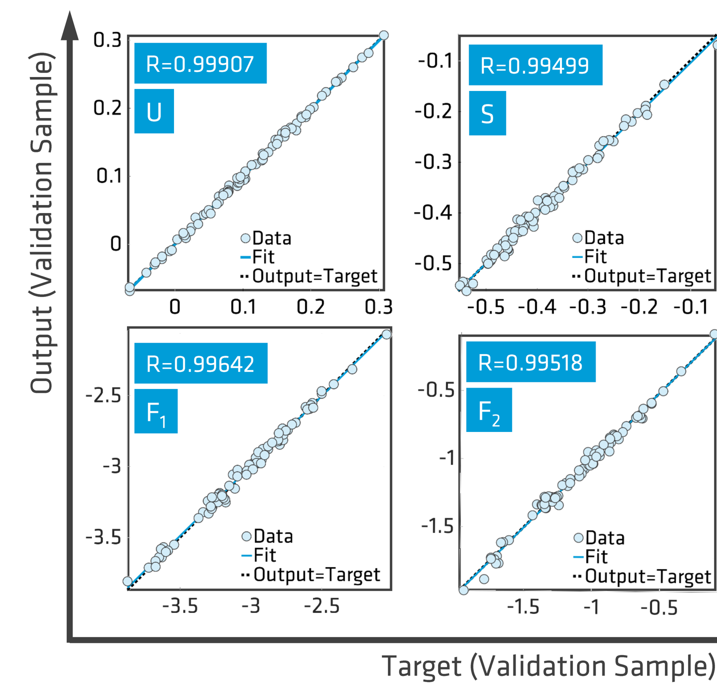
Genetic algorithm NSGA-II 3

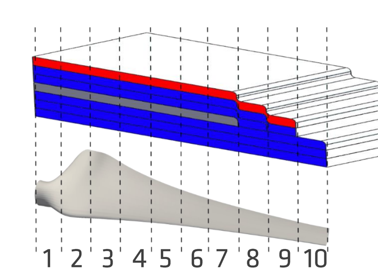
Non-dominated Sorting Genetic Algorithm-II [10].
Configuration: 64 individuals and 150 generations.
Total ANN evaluations: 9600

RESULTS

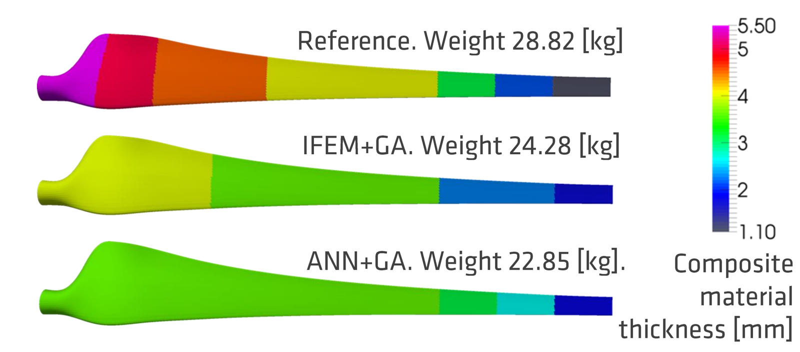
1







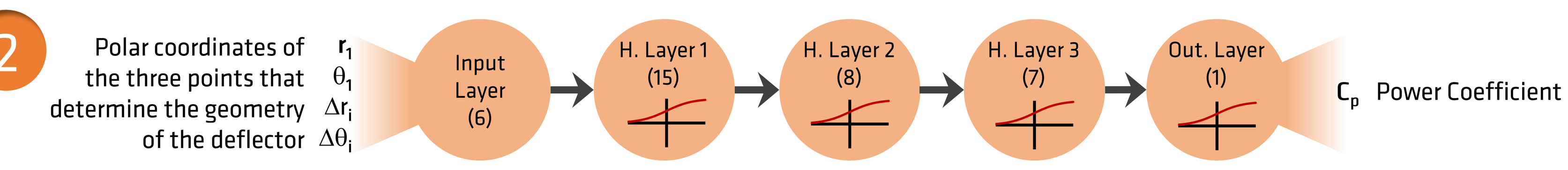
Characteristic	Reference [8]	IFEM+GA [9]	ANN+GA [1]
Number of plies	11	9	7
Blade weight	28.82 [kg]	24.28 [kg]	22.85 [kg]
Tip deflection	0.3500 [m]	0.3425 [m]	0.3560 [m]
1st eigenvalue	5.8575 [Hz]	4.4561 [Hz]	4.3932 [Hz]

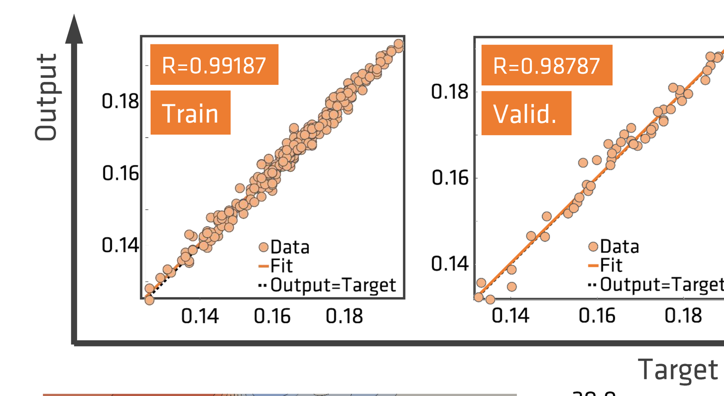


	U	S	F_1	F_2
MAE	0.006673 [m]	0.2888 [MPa]	0.3458 [Hz]	0.3588[Hz]
RMSE	0.008626 [m]	0.3624 [MPa]	0.4347 [Hz]	0.4445[Hz]

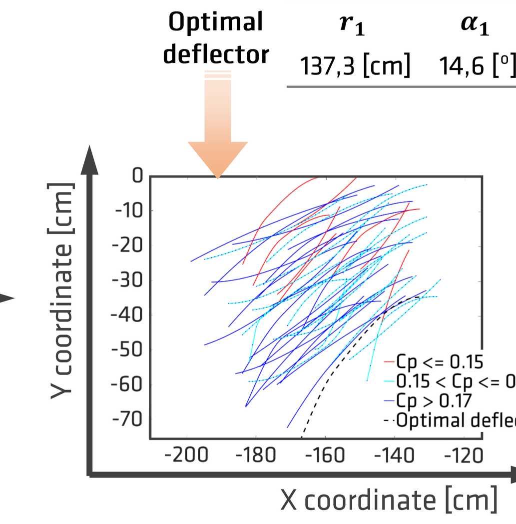
➤ The optimal blade weighs 22.85 [kg], being 20% lighter than the reference blade and 6% lighter that the former design with IFEM+GA. It also represents a reduction of 5 layers compared to the reference design, and of 2 layers compared to the design obtained using IFEM+GA.
➤ The use of the ANN+GA model allowed a 40% reduction of the computational cost in contrast with the simulation-based optimization approach (2500 versus 4800 simulations).

2

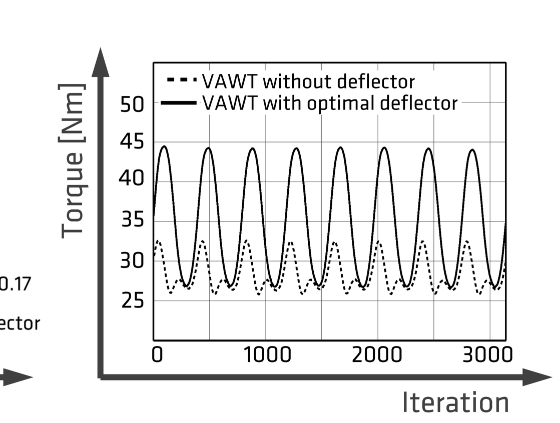




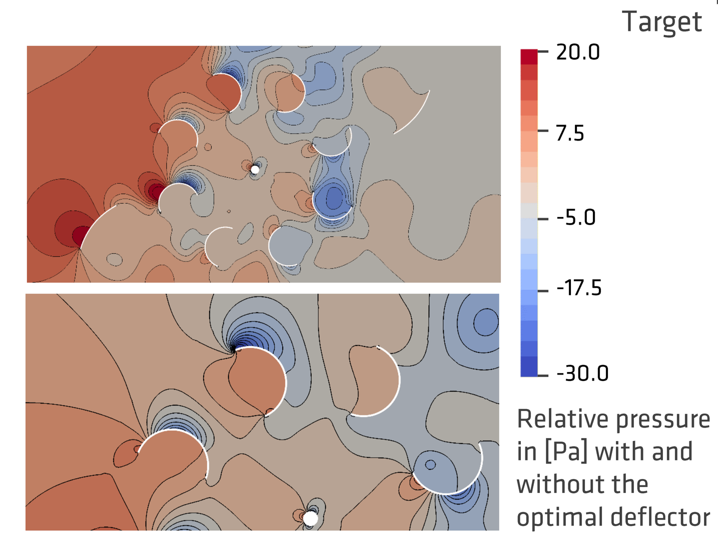
Optimal deflector	r_1	α_1	Δr_2	$\Delta\alpha_2$	Δr_3	$\Delta\alpha_3$	Cp
	137,3 [cm]	14,6 [°]	30,0 [cm]	5,0 [°]	16,9 [cm]	5,0 [°]	0,193



Validation sample and optimal geometries



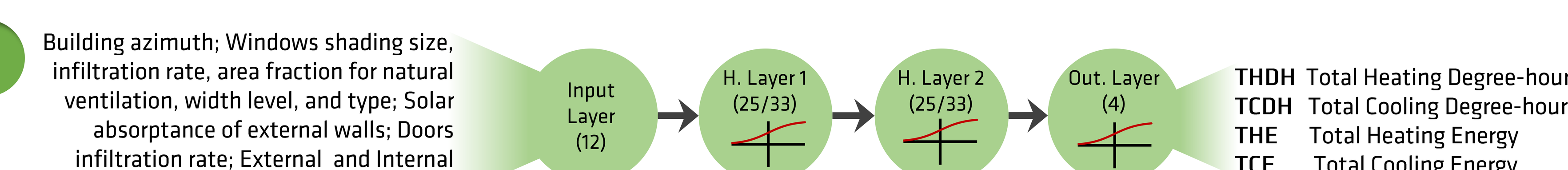
VAWT's torque during transient analysis

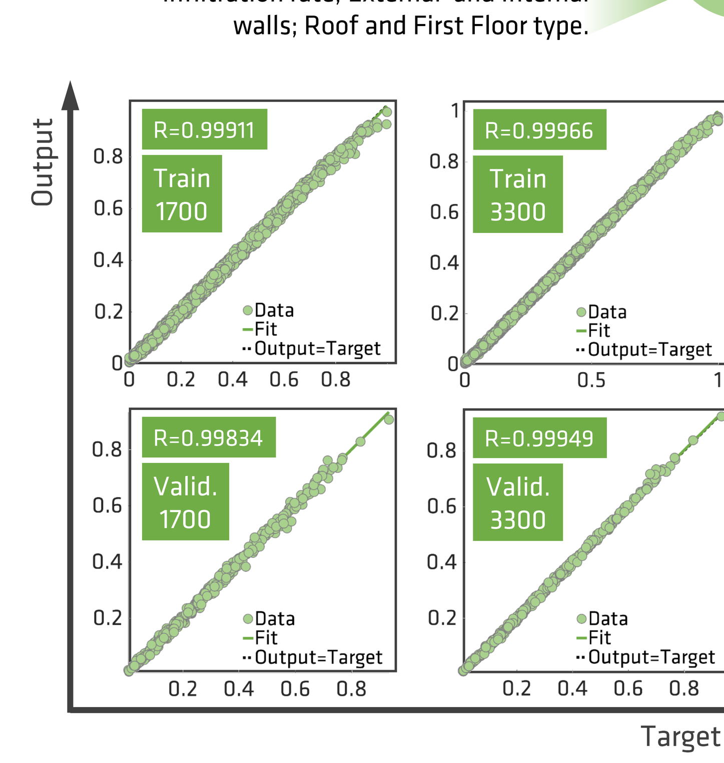


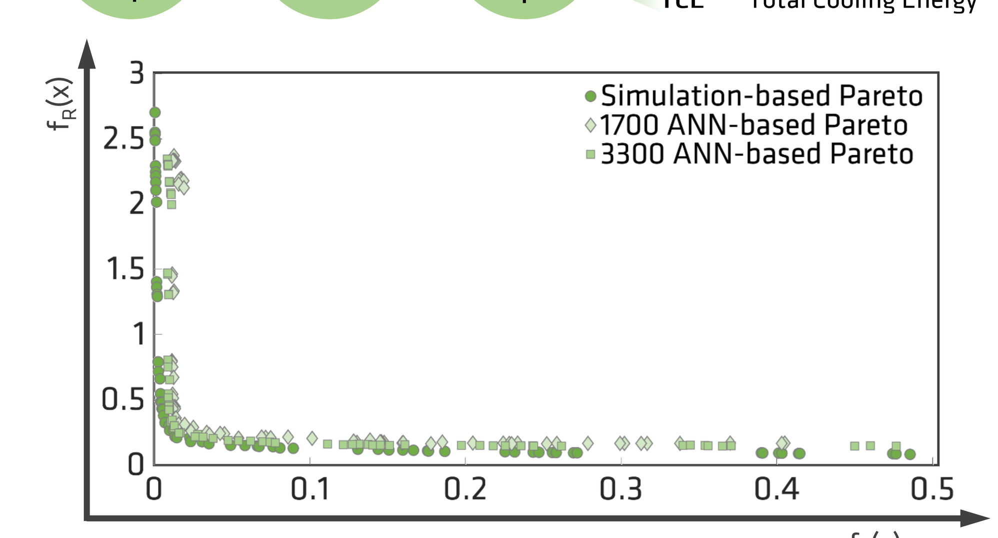
Relative pressure in [Pa] with and without the optimal deflector

➤ With the optimal designed deflector, the performance of the VAWT improves up to a 26%, being the Cp of the VAWT without deflector 0.153.
➤ The deflector increases pressure gradient between the concave and the convex surface of the VAWT blades, which translates in a improvement of the torque.
➤ The use of the ANN+GA model took a total of 11 days and 16 hours (350 CFD simulations, 1.19 hours of ANN training, 4 seconds of GA optimization), while a simulation-based optimization approach would need 323.2 days (4848 CFD simulations, 1,6 hour each).

3







➤ Both ANN metamodels presented an excellent performance while evaluating the validation sample.
➤ The Pareto front obtained with the ANN trained with the 3300 sample is close to the simulation-based Pareto.
➤ The use of the ANN+GA model allowed a 68% reduction of the computational cost in contrast with the simulation-based optimization approach (9600 versus 3300 simulations).

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