Recent Progress in the Modeling of Detrimental Effects of Wind on ACC Performance

ACC User Group meeting *- London, England, United Kingdom*

Author: C. Bianchini

24/07/2024

Outline

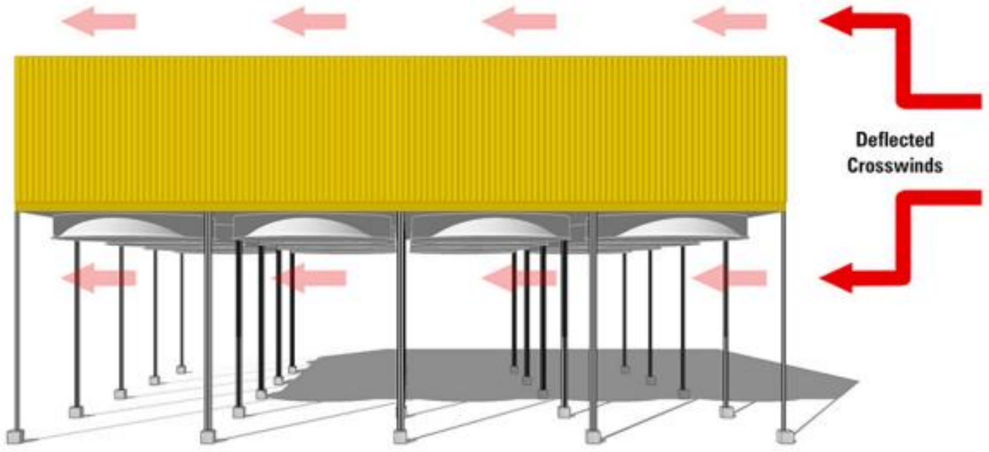
- Context

- Achievements
  - Definition of a High-Fidelity CFD procedure and generation of a large performance database (High Performance Computing)
  - Development of a digital-twin thermally coupling the air side and the steam side
  - Validation of a practical procedure to estimate the fluctuating fan blade load
  - Identification of an innovative windshield concept
    - Minimize the fluctuating blade load

- Closure

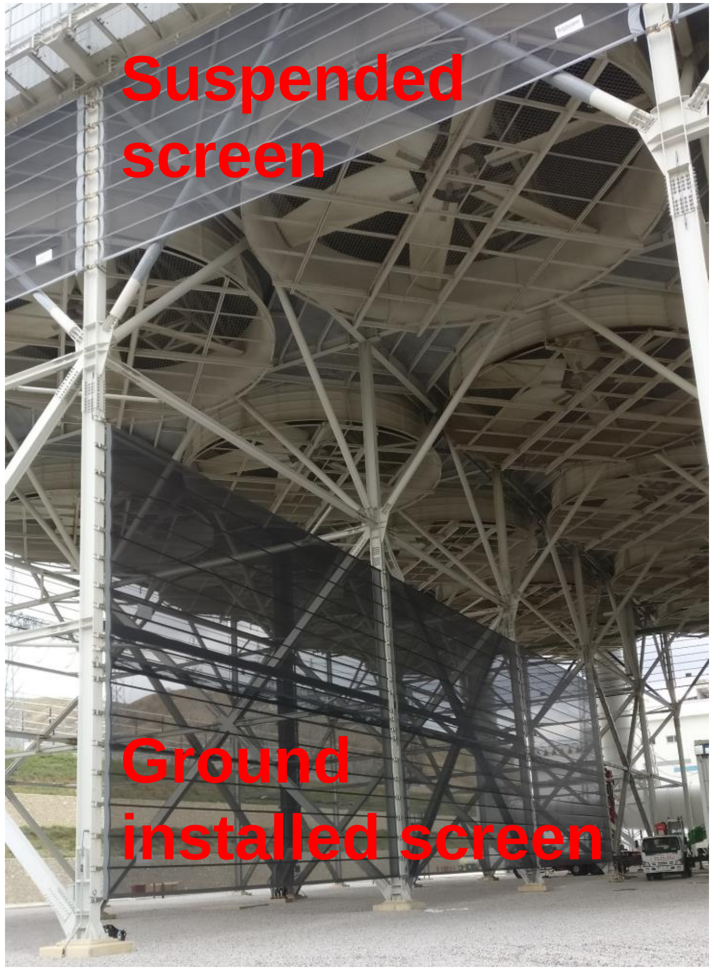
Context

- ACCs are characterized by complex aerodynamics
  - Large diameter
    - High hub-to-tip velocity difference
    - Low solidity and blade stiffness
  - Interaction with neighbouring fans
    - High lateral crossflow
  - High influence of environmental conditions
    - Ambient temperature
      - Impact the ST back-pressure
        - Thermal equilibrium depends on air-steam temperature difference
    - Wind
      - Increase cross flow below the fan deck
        - Reduce the air flow at the fan
      - Bend plume trajectories
        - Promote recirculation of spent air
      - Generate imbalance between windward and leeward side of each fan
        - Especially on the windward side fans
        - Increase the blade load periodic fluctuations
      - Blows with gusts
        - Introduce random unsteady fluctuations



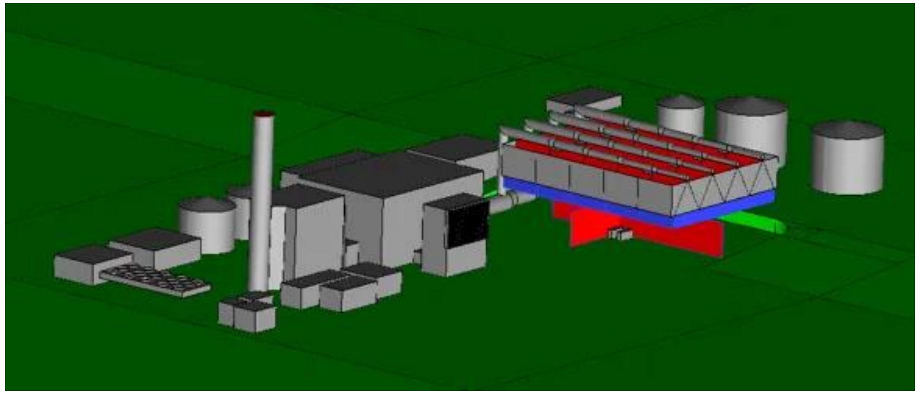
Challenge

- Objectives:
  - Estimate the detrimental effect of wind on ACC performance
  - Identify effective mitigation strategies
- Focus on windshields as most practical solution for many applications:
  - Wind shields can:
    - Reduce the crosswind below the fan deck
    - Divert the horizontal momentum of wind upwards
    - Block the hot air re-entering below the ACC
  - Cost effective solution:
    - Simple technology: PVC-coated polyester fabrics
    - Directly installed onto the ACC structure
    - Long life, no maintenance
  - Wind shields effectiveness depends on:
    - ACC (and plant) characteristics
    - Screens size and porosity
    - Local weather conditions



Challenge

- Shields design procedure used in the past are somewhat uncertain:
  - Based on experience and historical customer satisfaction
    - Hardly quantifiable benefits
  - Difficult to generalize design rules for different ACCs
  - CFD based design limited to simplified approaches to model fan and bundles due to computational complexity
    - Large fan dimensions
    - Large number of fans
- The high-fidelity procedure should overcome the limitations of current methodology:
  - Rely on OEM data estimations
    - Determined for isolated fans, not available outside the stable range, evaluated with undisturbed flow
  - Be limited to the air-side
  - Not provide direct measure of the fluctuating blade load

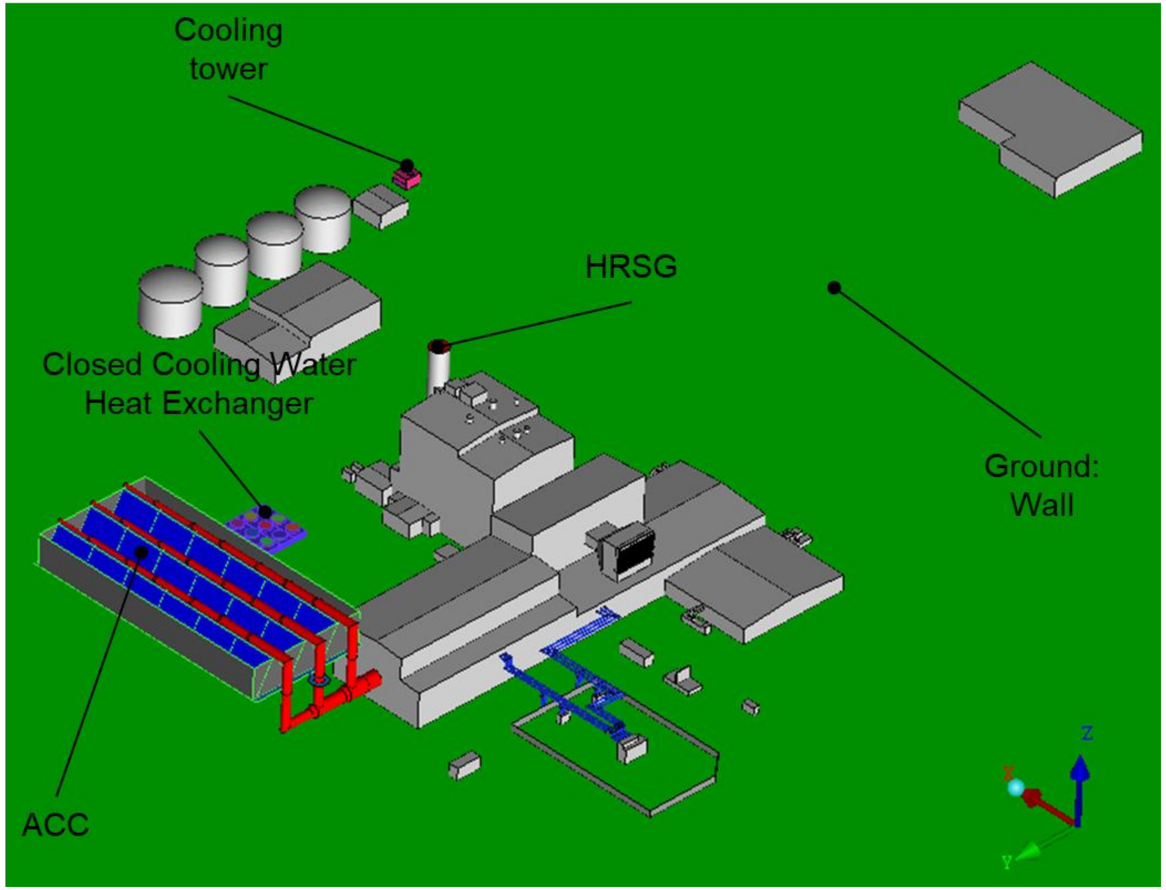


Specific objectives

- Identify a representative test case
- Define a High-Fidelity CFD procedure
- Generate a large performance database to well estimate wind losses
- Identify the optimal windshield configuration to recover such losses
- Complete the database with the performance with the windshields
- Implement a digital-twin for the thermal coupling of the air and the steam side
- Analyze the benefits of the windshields on the fluctuating blade load and validate the reduced complexity CFD method
- Identify an innovative windshield concept able to minimize the fluctuating blade load

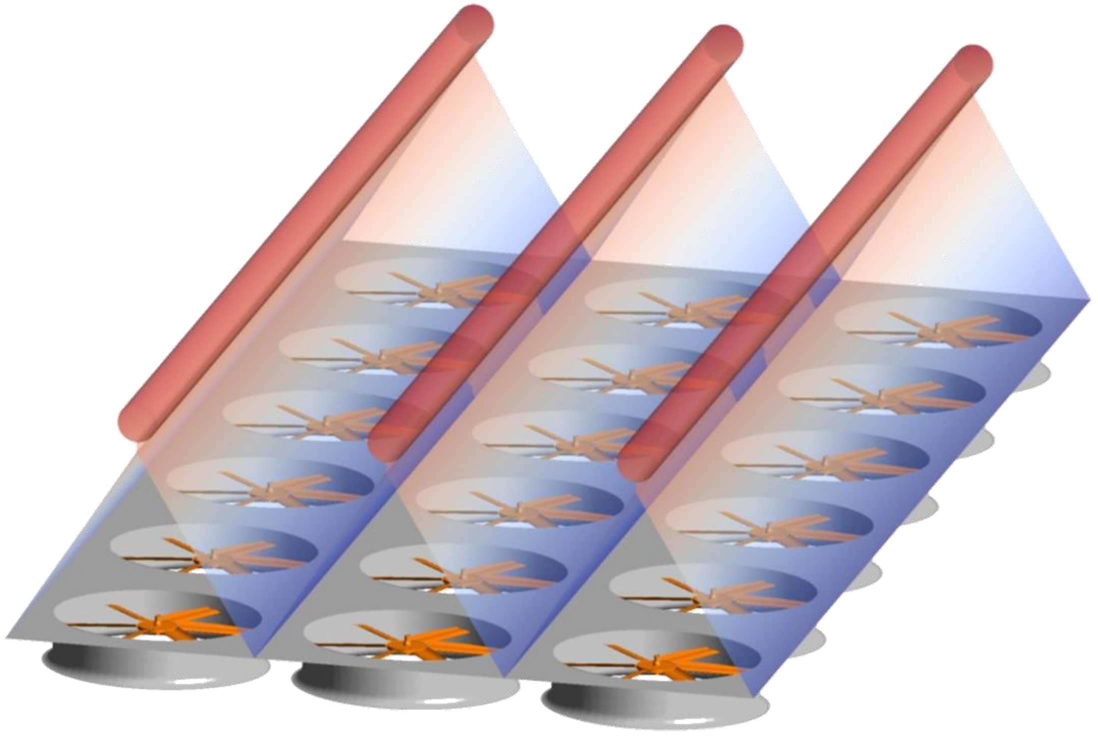
Modelling

- Identification of a representative test case
  - ACC definition based on existing equipment
    - 18 fans: 6 rows x 3 streets
    - A frame layout
    - Thermal duty: 202.84 MW (11.4 MW per module)
    - Air side temperature increase: 18.5 K
  - Fan
    - Diameter: 10.4m
    - 6 blades
    - Rotational speed: 77 rpm (BPF = 7.7 Hz)
    - Nominal duty point: 520 m^3/s at 85 Pa
  - ACC structure
    - Fan deck level: 19 m
    - Bay dimensions: 14.4 m x 12.7 m
    - Overall dimensions: 87 m (L) x 39 m (W) x 29 m (H)
  - Plant layout
    - No surrounding buildings or machinery
      - Decrease computational complexity
        - Only flat ground considered
        - Focus on wind from 1 quadrant only



Modelling

- Definition of a high-fidelity procedure
  - Sliding mesh methodology
    - Detailed 3D modelling of all 108 fan blades
    - Unsteady rotating domains modelling
      - 18 rotating + 1 stationary domains
  - Time advancement: dual iteration method
    - Second order
    - Time step size: 13 ms
      - 10 timesteps/BPP
    - 3 inner iterations/time step
      - SIMPLE algorithm
  - Buoyancy forces activated
  - Simulation strategy
    - 10 full rotation simulated
    - Initialization from frozen rotor steady solution
  - Ansys Fluent 2021R1

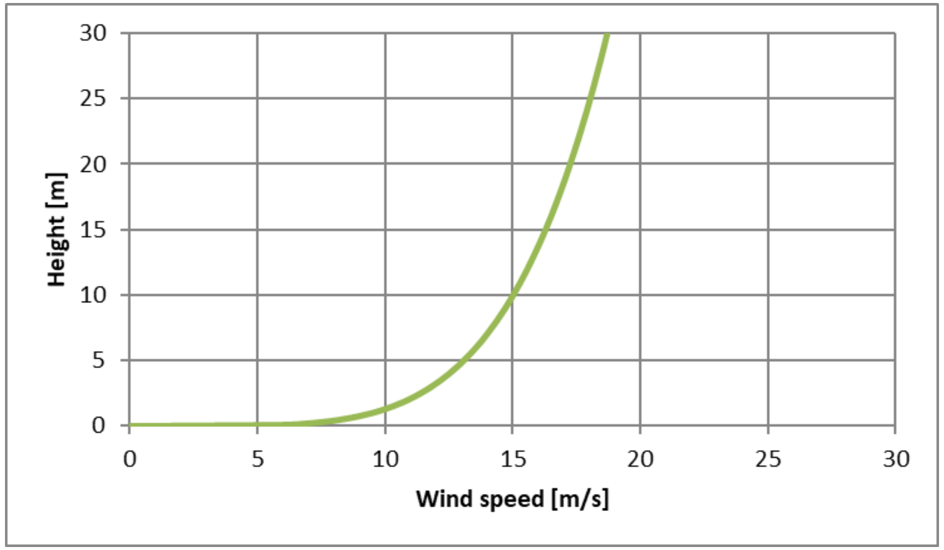


Mesh

- Hybrid tetrahedral/prismatic mesh
  - 6 prisms layers
- Grid of a single blade
  - 1.3M cells
  - y^+ O(100)
- Replicated:
  - 6 times rotationally (one fan)
  - 18 times bi-linearly (6x3 ACC arrangement)
- External environment box: 1000 m (L) x 1000 m (W) x 500 m (H)
- ACC walls, bundles and windscreens: thin walls
- Total mesh count: 162M cells
- Computational cost of each case: 2500 core hours

Boundary conditions

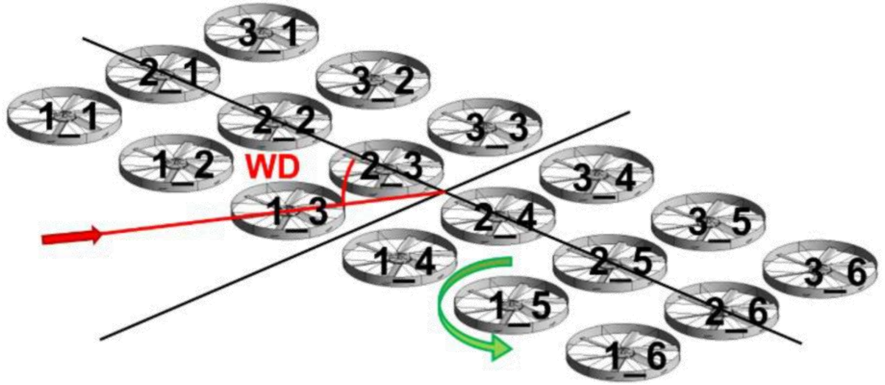
- Bundle
  - Radiator model
    - Specified pressure drop coefficient
    - Fixed outgoing air temperature
- Windscreens
  - Pressure-jump model
    - Specified pressure drop coefficient
      - Available data from experiments at Stellenbosch University
      - Fabrics with solidity 50, 60, 75%
- Wind profile
  - Applied in the far field
  - Power law profile
    - $V(z) = WS\left(\frac{z}{z_{ref}}\right)^{\alpha}$
  - α depends on boundary layer stability and surface roughness
    - α = 0.2 valid for slightly unstable BL in urban environment and slightly stable BL in rural environment
  - Inlet turbulence: 5%



Applied wind profile at WS = 15 m/s

HPC Database

- Wind losses without windshields
  - Reference condition is WS = 3 m/s and WD = 90 deg
    - Major losses occurs on the windward side (street 1)
    - Recirculation is low for all fans
  - Losses increase largely with windspeed and are maximum at 90 deg

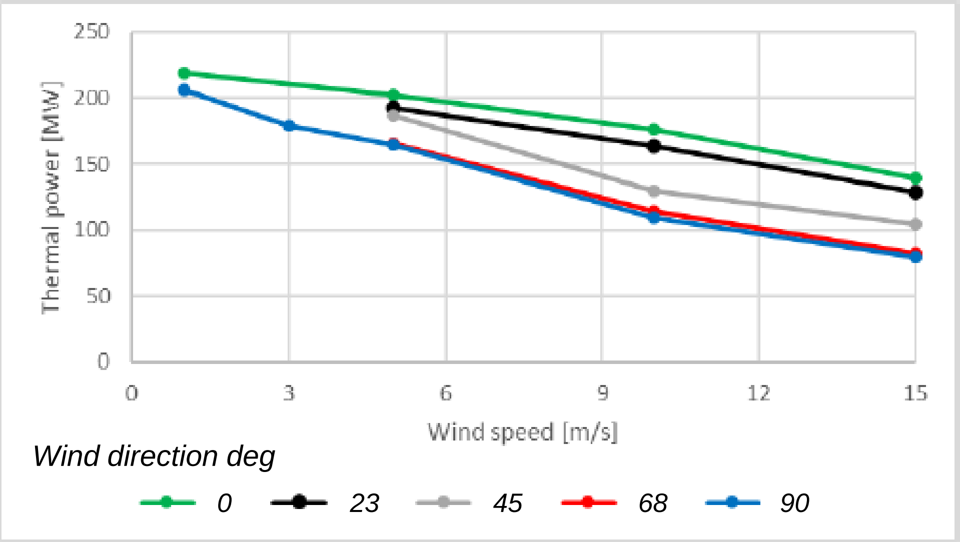


Fan flow rate / nominal flow rate %

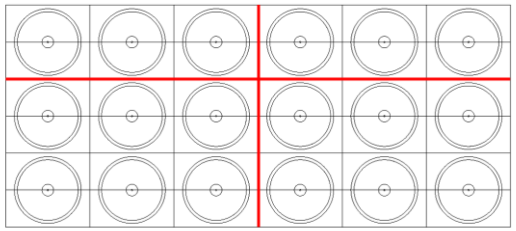
Street/Row	1	2	3	4	5	6
3	106.55	108.57	107.56	107.96	108.39	103.13
2	103.25	105.14	101.89	97.35	102.68	96.58
1	71.49	57.30	50.28	44.19	42.86	79.73

Recirculation %

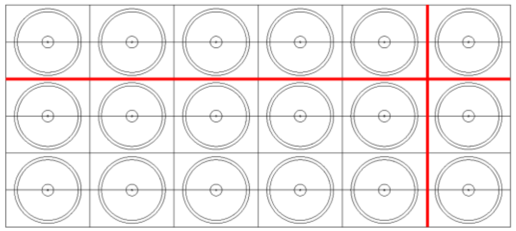
Street/Row	1	2	3	4	5	6
3	3.46	0.00	0.00	0.00	0.00	1.53
2	0.16	0.04	0.12	0.00	0.00	0.12
1	0.51	1.50	1.22	0.86	0.77	0.15



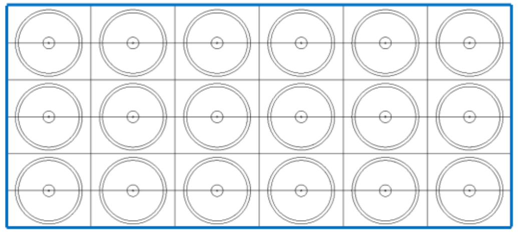
- Identify optimal wind screen layout
  - Several windshield layouts were tested at the most critical wind condition (WS 10 m/s – WD 90°)
  - Layouts: cruciform, perimeter, one-bay-back, skirt, combined
  - Porosity: available commercial polyester fabrics M50, M60, M75 (increasing mesh solidity)
  - Variable dimensions



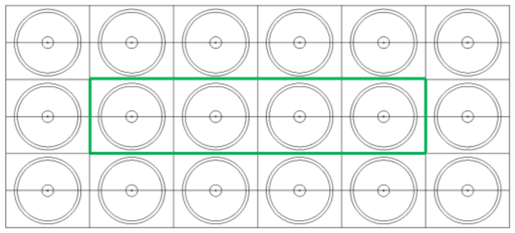
cruciform



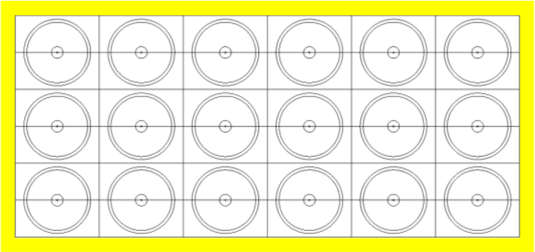
cruciform north



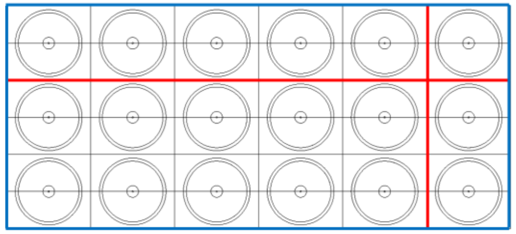
perimeter



one-bay-back



skirt

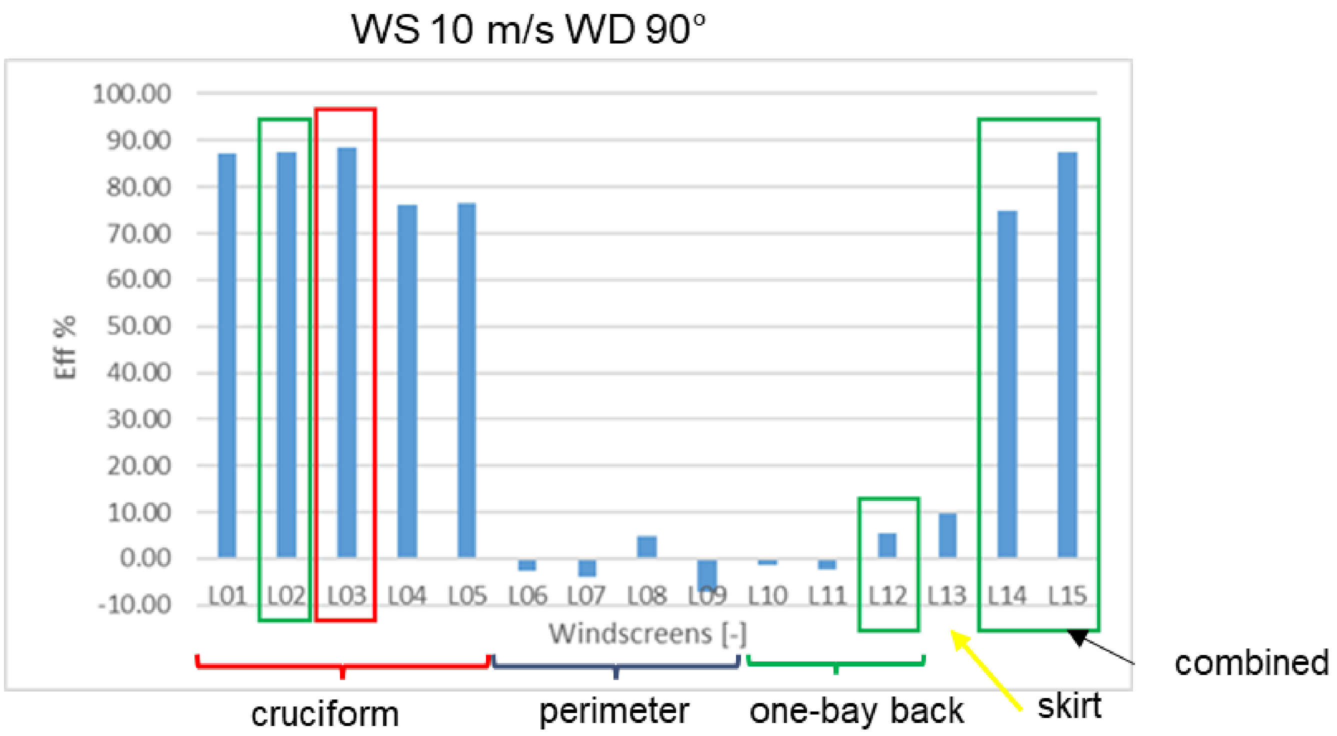


cruciform+perimeter

label	model	solidity	Height
design	-	-	-
L00 - 1 m/s	-	-	-
L00	-	-	-
L01	crux	M75	50% of fandeck
L02	crux	M75	70% of fandeck
L03	crux	M75	70% of fan deck (north side)
L04	crux	M60	70% of fandeck
L05	crux	M60	80% of fandeck
L06	perimeter	M50	2m below fan bell
L07	perimeter	M60	2m below fan bell
L08	perimeter	M60	4m below fan bell
L09	perimeter	M75	4m below fan bell
L10	one_bay_back	M60	2m below fan bell
L11	one_bay_back	M75	2m below fan bell
L12	one_bay_back	M60	4m below fan bell
L13	skirt	M75	2m outside of ACC
L14	crux + perimeter	M75 + M60	70% of fan deck + 4m below fan bell
L15	crux + skirt	M75 + M75	70% of fan deck + 2m outside of ACC

HPC Database

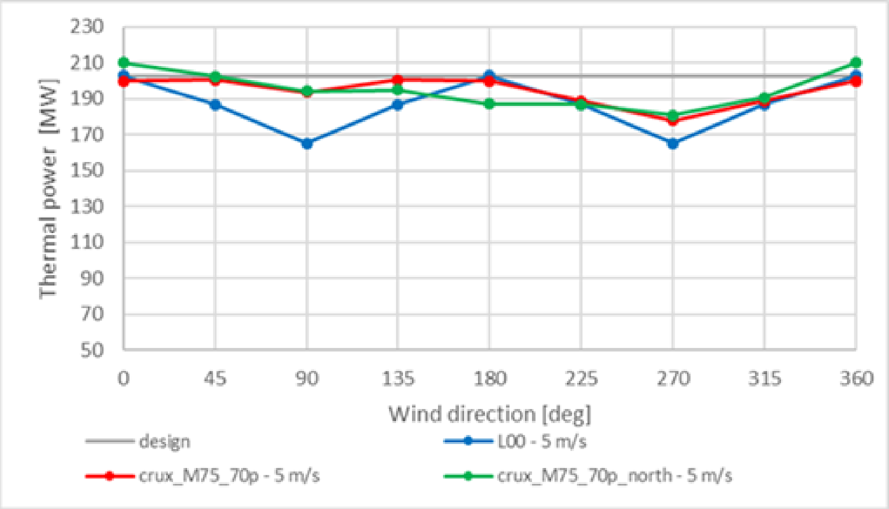
- Identify optimal wind screen layout
  - Cruciform based screens have an effectiveness (recovery of wind losses) close to 90%
    - Best result for thermal power effectiveness is obtained for L03 (cruciform only – north side)
    - One-bay-back and perimeter screens alone do not provide significant thermal improvements

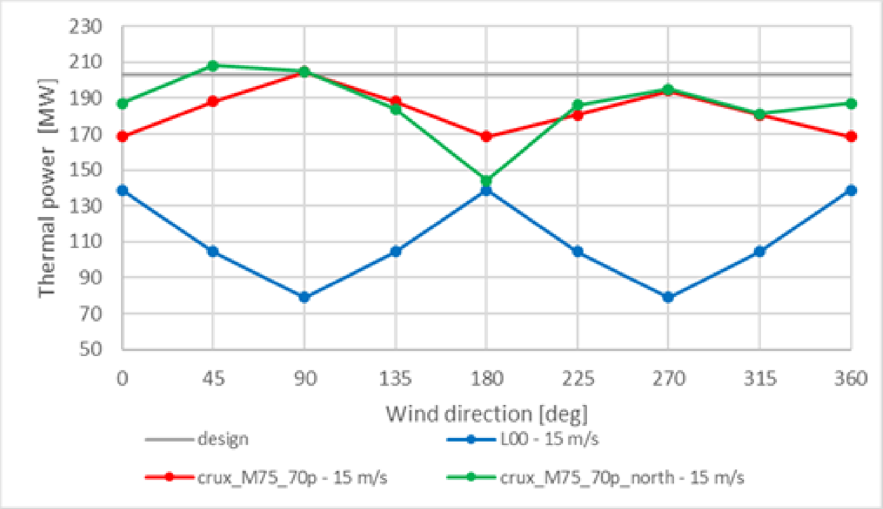


HPC Database

- Full test matrix of wind directions and speeds is generated to feed the digital twin
  - Wind direction: every 45 deg
  - Wind speed: 5, 10 and 15 m/s nominal wind speed
- Best shield configuration was tested
  - North-South symmetric cruciform was selected as a more robust option at different wind directions
- When the wind blows along the principal ACC axis (0 and 180 deg):
  - Much lower wind losses and reduced benefits thanks to the windshields
- With inclined wind direction the benefits are still quite high

5 m/s

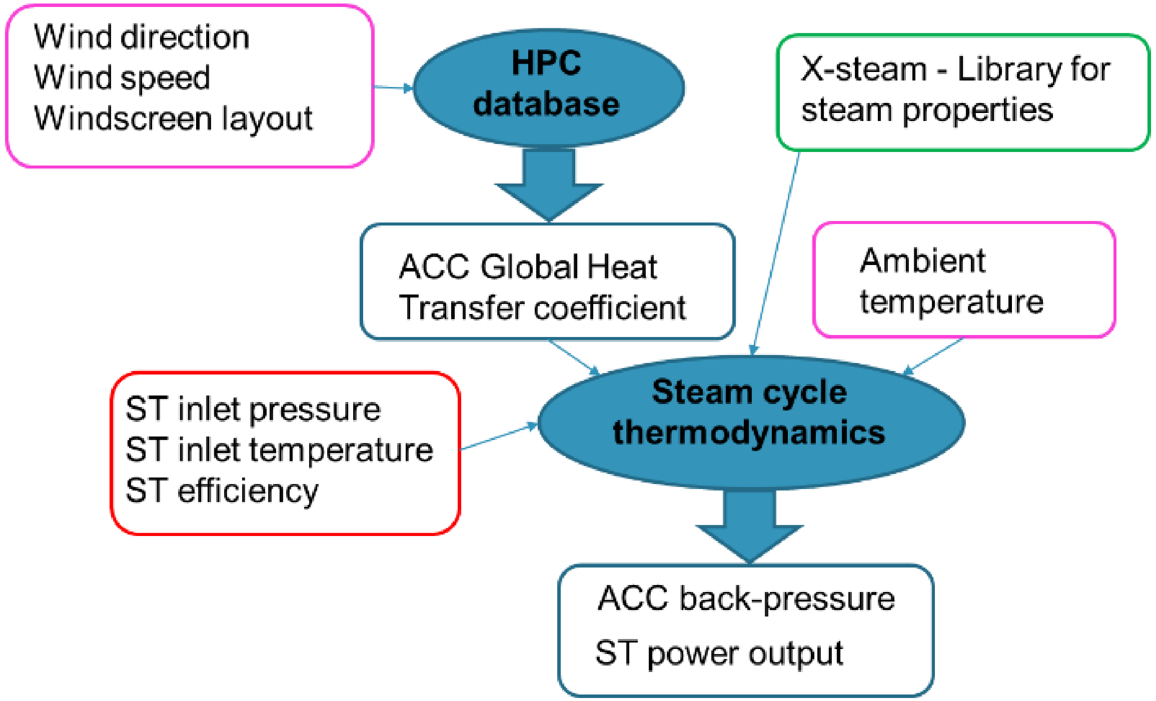




15 m/s

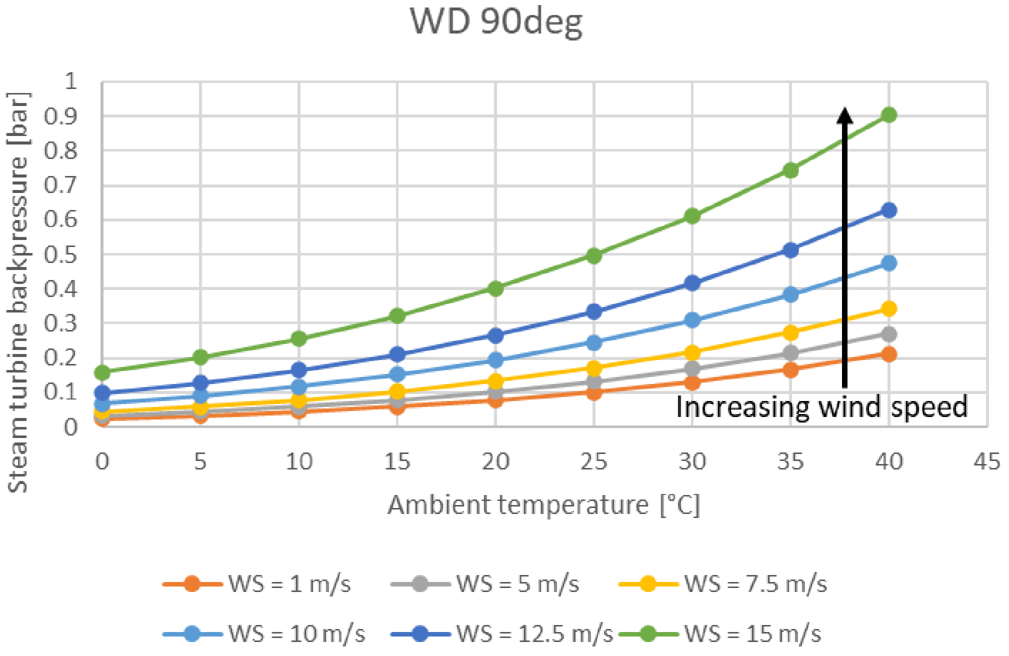
Digital twin

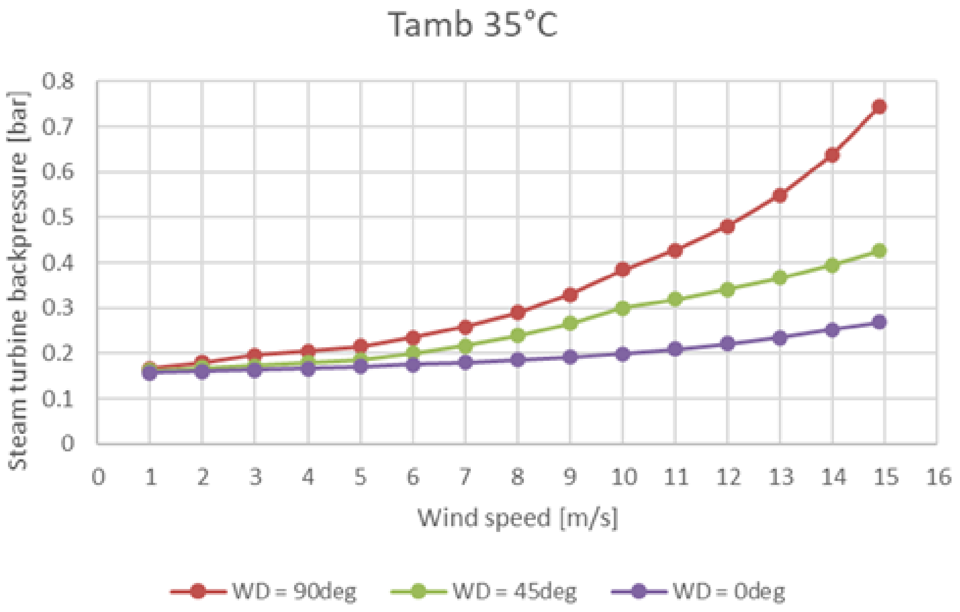
- The digital twin solves for the thermal equilibrium between the condensing steam power and the air side cooling
  - Iterative convergence loop for the ACC back-pressure
- Steam side:
  - ST expansion with fixed inlet condition and isentropic efficiency
- Air side:
  - Heat balance with ACC Global Heat Transfer Coefficient from the CFD analysis database
    - Database interrogated with: wind direction, wind speed and windscreen layout
    - Interpolation permits to expand the database to virtually any weather condition
- Implemented in a spreadsheet:
  - Easily customizable for each project and for non-specialist
  - Fast and automatic through the implementation of VBA macros
- Process thousands of operating points in just few minutes:
  - Actual weather time series used as weather forecasts to evaluate the yearly benefits thanks to windscreens



Digital twin – Steam side L00

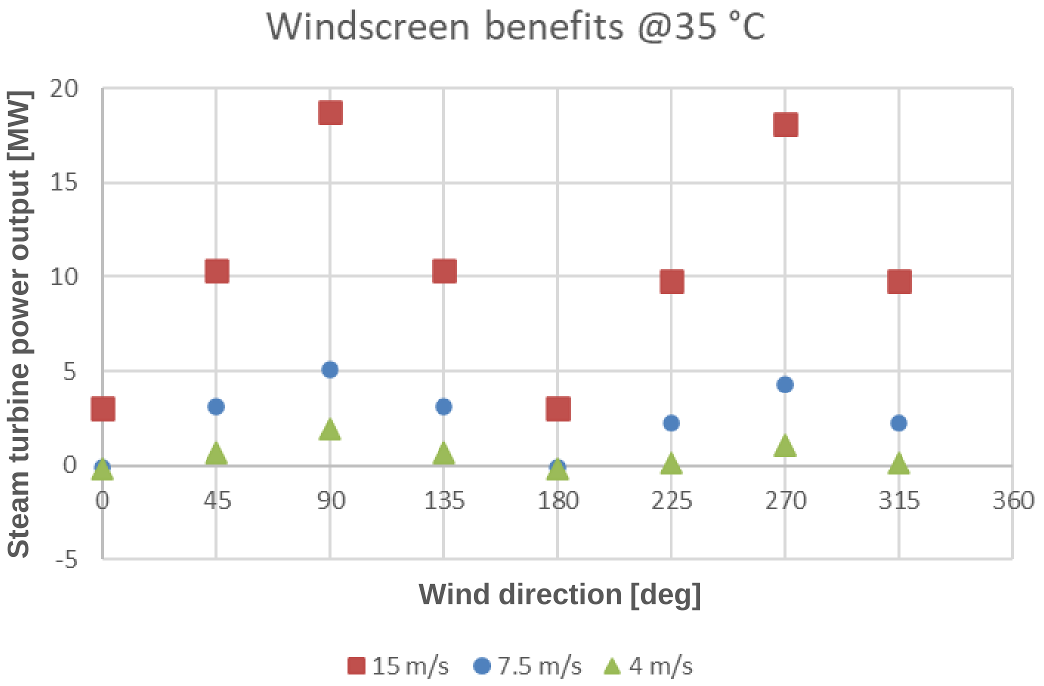
- ST backpressure increases largely with:
  - Ambient temperature
  - Wind speed
- It is maximum for winds blowing perpendicular to the main ACC axis





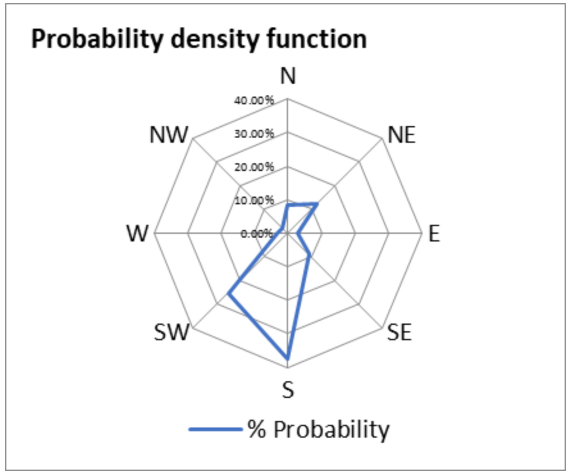
Digital twin – Steam side L02

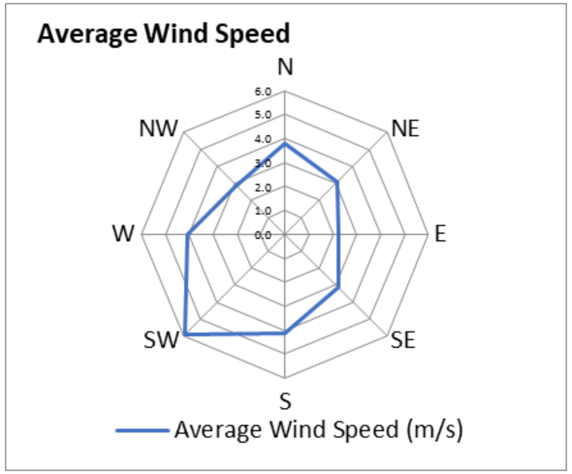
- The improvements thanks to windshields (L02-L00) are maximum at 90 deg
- Increase largely with wind speed



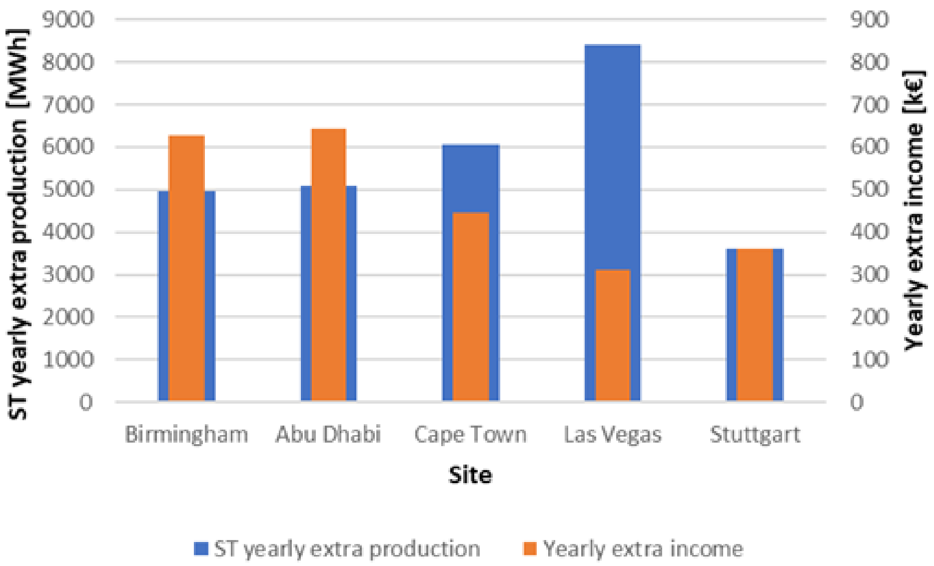
Digital Twin – Steam side L02

- Several sites around the world were selected as typical examples of different regions
  - Ambient conditions, energy selling price, installation costs
- Extra income is mostly related to energy selling price
- Installation costs are variable only for shipping and labour (±20% variability)
- All site have a payback lower than a year
  - Hot and high wind season is responsible for much of the gains



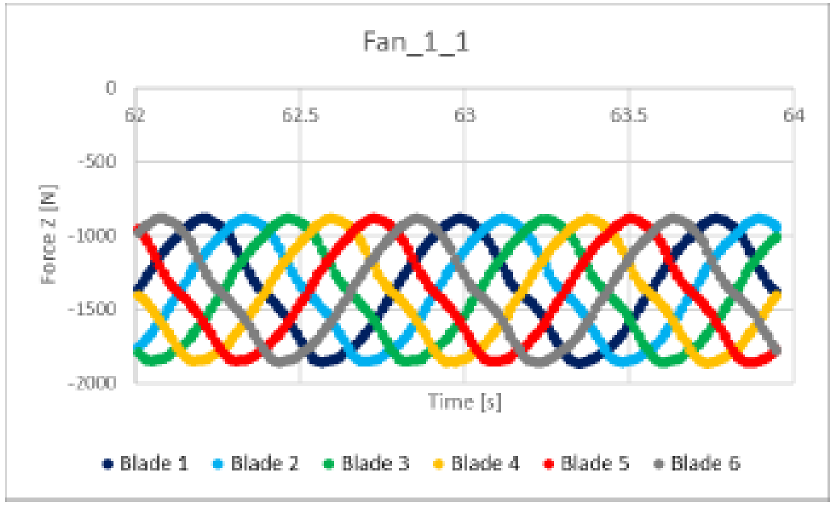


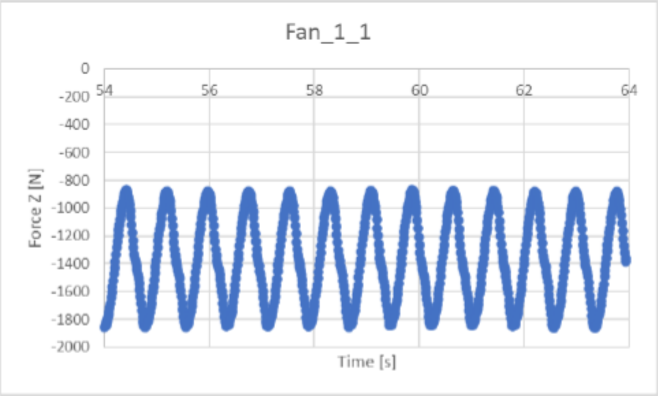
Yearly wind statistics in Las Vegas

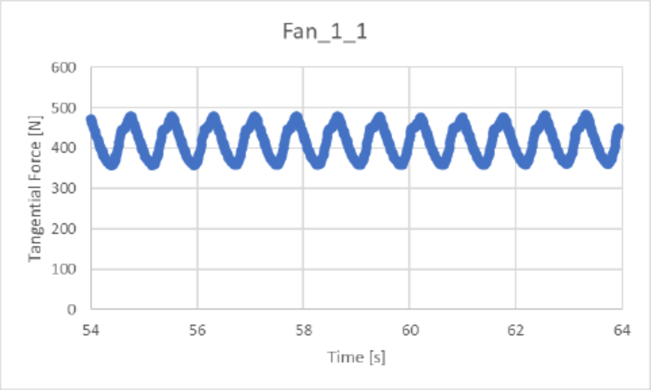


Fluctuating blade load

- Unshielded configuration
  - Reference condition is WS = 3 m/s and WD = 90 deg
  - The blade forces are equal just shifted in time by one BPP
  - The vertical force is much higher than the tangential one
    - Both in magnitude and fluctuations
    - Force Z used to assess fluctuating mechanical forcing





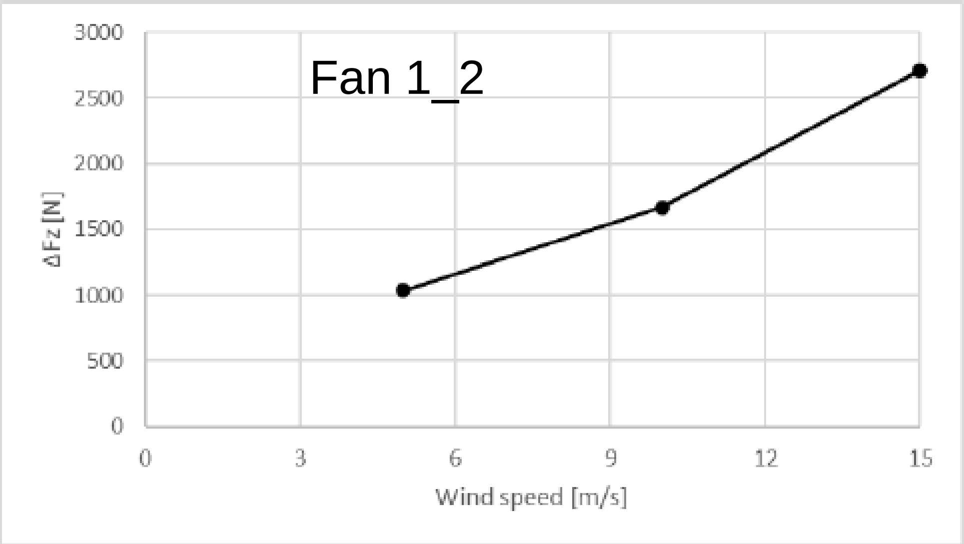


Fluctuating blade load

- Unshielded configuration
  - Corner fans are characterized by the highest fluctuations
  - Fluctuations increase significantly with wind speed

Vertical force fluctuations amplitude [N]

Street\Row	1	2	3	4	5	6
3	375	549	546	481	538	881
2	463	686	679	610	487	827
1	992	612	685	539	506	729

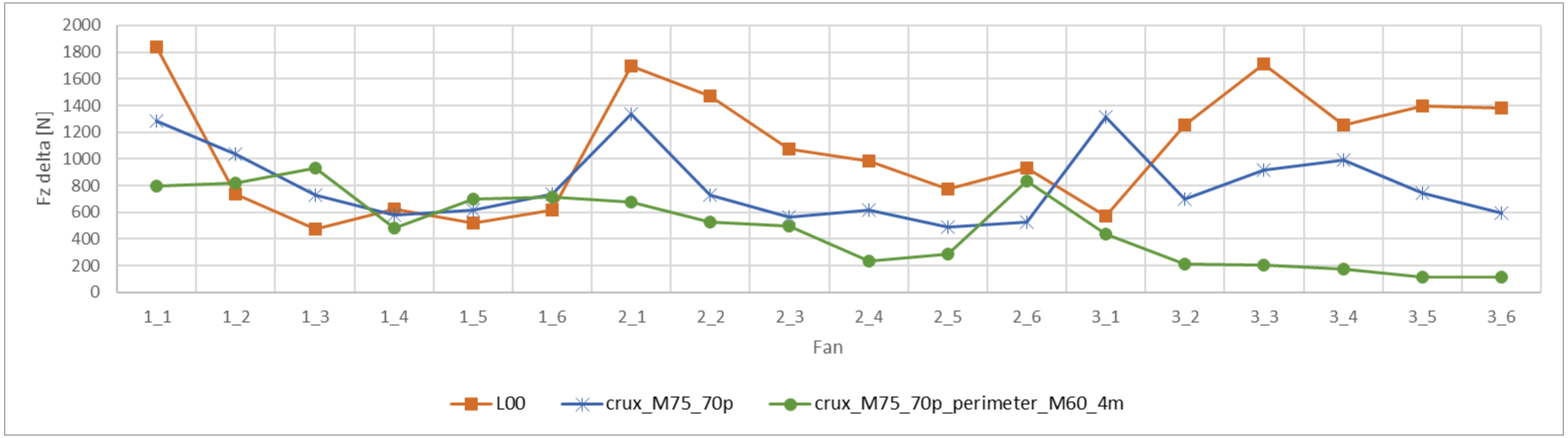


Vertical velocity oscillations – WD 23 deg

Fluctuating blade load

- Windshielded configuration
  - The cruciform screen reduces the peak oscillations
  - Perimeter screens introduce a further damping
    - Beneficial also for wind gusts
  - On fans with low fluctuating load the impact of screens is negligible

WS 10 m/s WD 45°



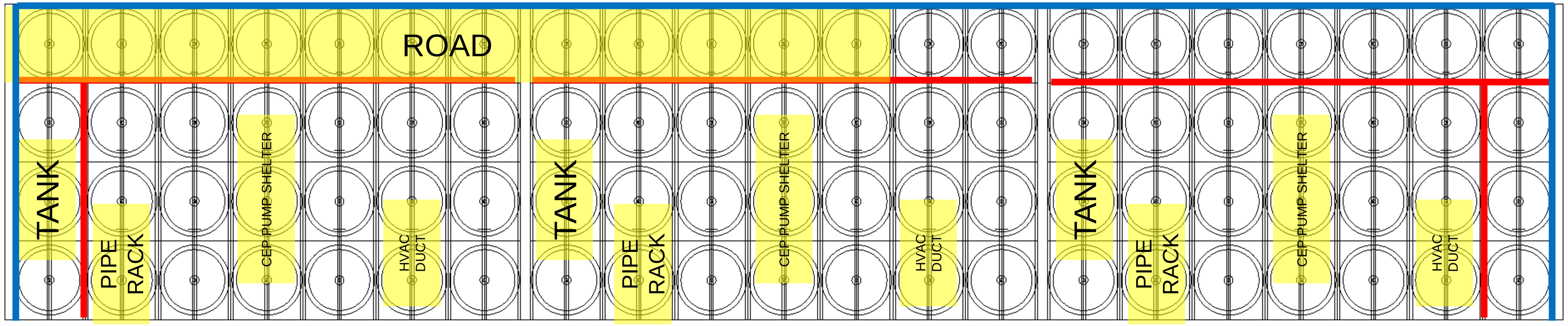
Windscreen layouts

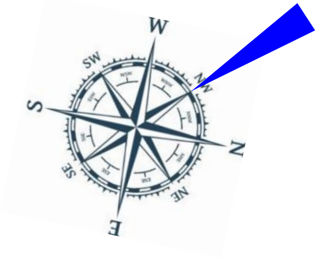
- Test case is a 3 units ACC (4x7 layout)
- Wind is blowing inclined to the main axis
- Among many layouts, L04 was suggested to minimize load fluctuations

Cruciform M75 19.33m (70% fan elevation)

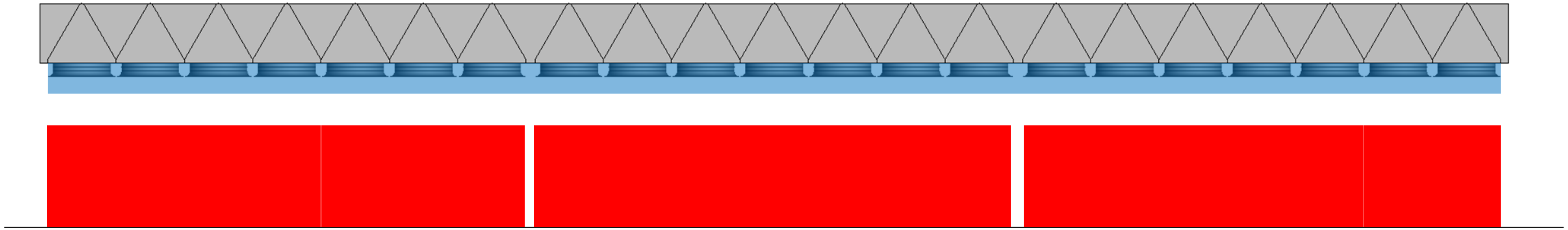
Perimeter M60 4.39m (2m under fan bell)

Top view





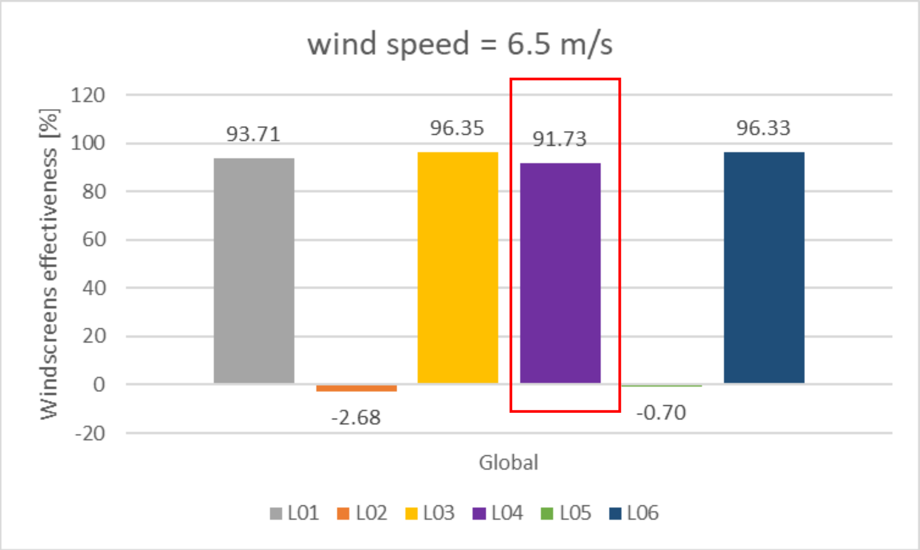
East view



Windscreen layouts

Wind
315°

- Close to best in overall thermal performance
- More uniform distribution over the various cells



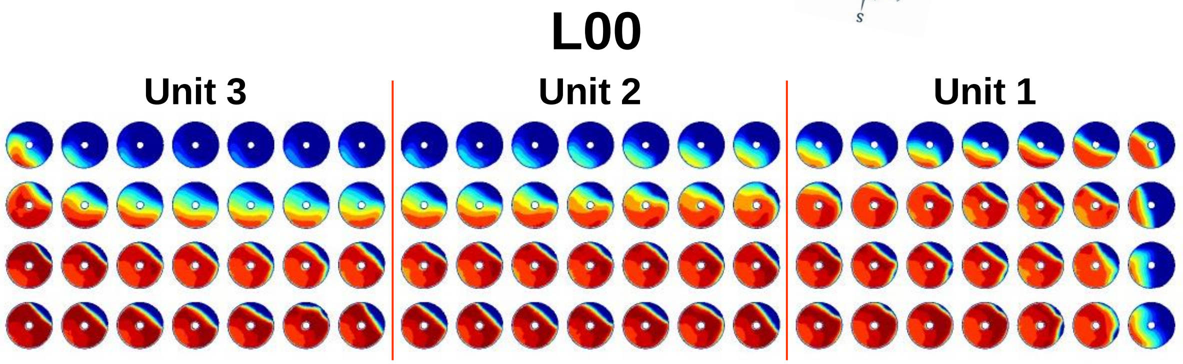
Unit	L00				L03				L04			
Unit 1	36.40	26.73	22.61	34.43	50.58	46.04	36.58	44.86	60.02	50.89	55.55	62.82
	39.68	73.65	76.61	92.10	61.94	102.78	94.40	90.22	67.78	91.81	92.42	98.52
	29.86	76.70	88.21	96.26	70.60	103.34	89.25	91.90	71.44	82.91	68.34	82.13
	19.67	81.04	89.41	104.01	71.66	106.29	96.35	93.94	71.03	88.01	73.84	81.22
	15.53	80.16	91.17	100.88	67.12	98.08	91.85	95.14	72.85	91.80	83.68	85.26
	14.88	74.31	93.99	99.94	56.61	86.16	87.53	88.57	75.49	93.87	86.51	83.78
	16.69	68.93	97.60	98.41	43.81	88.80	90.49	91.31	79.21	96.44	90.29	78.00
Unit 2	15.39	66.57	89.86	91.66	44.37	101.49	98.78	93.21	77.37	97.65	93.06	80.30
	11.89	65.01	92.65	98.93	48.18	105.92	94.87	88.58	79.58	95.46	97.03	88.57
	9.41	63.14	94.55	95.48	54.37	106.68	100.32	94.13	79.29	91.43	88.50	88.25
	7.74	61.47	95.29	93.02	58.90	106.60	97.76	97.54	79.59	91.51	84.84	82.30
	5.40	58.46	95.44	92.07	57.17	100.68	92.96	91.32	80.55	94.25	85.70	75.06
	5.00	55.05	95.61	92.26	52.47	91.50	88.97	89.04	81.31	95.85	84.90	72.90
	4.14	53.77	94.95	90.35	50.38	100.26	95.18	89.29	82.70	95.64	81.72	75.88
Unit 3	2.28	51.91	86.23	91.03	52.10	101.75	100.79	91.61	78.17	91.74	85.99	81.06
	2.31	46.30	86.05	100.39	58.21	104.25	96.77	90.76	79.88	94.33	89.34	77.18
	2.14	46.49	88.17	92.71	62.94	106.63	92.58	90.53	79.49	92.71	85.47	64.14
	2.47	47.36	89.91	88.72	67.69	109.94	101.59	94.30	79.62	89.43	77.01	70.81
	3.73	51.59	92.13	89.67	68.35	104.98	98.32	89.11	82.04	93.27	79.73	81.33
	6.03	61.20	96.86	94.42	65.56	94.56	92.20	85.70	86.80	102.84	95.78	93.66
	29.56	84.34	104.27	101.27	77.66	102.72	97.63	85.18	97.14	103.17	92.47	87.12

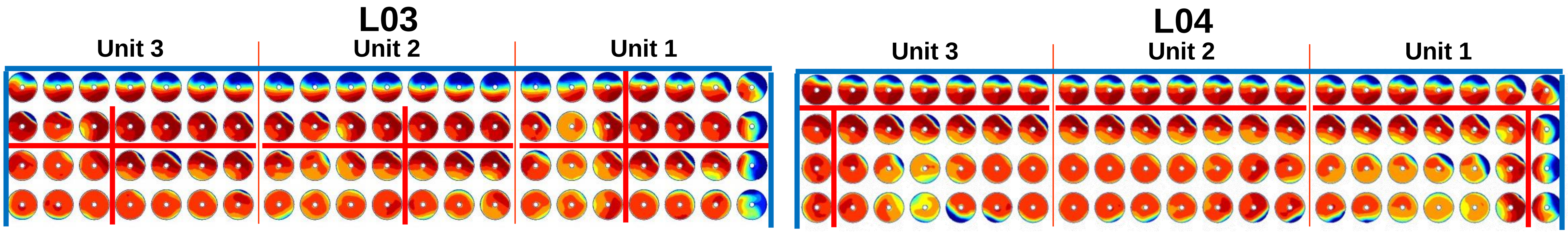
$$TP_{\%} = 100 \cdot \frac{TP}{TP_{des}}$$

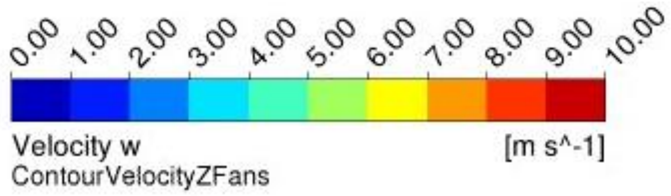
0% **50%** **100%**

Windscreen layouts

- Reduced flow imbalance on windward fans







Conclusions

- An High-Fidelity CFD procedure was defined based on sliding mesh technology
- An optimal windshield layout capable to recover most of the losses was identified
- A complete map of the improvements achievable on the ACC global heat transfer coefficient was computed
- A digital twin of the ACC steam side thermodynamic behaviour was implemented
  - Calculation of the thermal equilibrium between air and steam
  - Provides the ACC performance in terms of ST turbine output and ACC
  - Fed with weather forecast, provides aggregate monthly/yearly extra energy production thanks to the windscreens
- Several sites were selected worldwide to test the profitability of the proposed solution under different weather conditions and energy selling price
  - For all tested sites the estimated payback is shorter than a year
- The High-Fidelity procedure permitted to verify directly the fluctuating blade load
  - The beneficial impact of the windshields was directly assessed
  - The obtained data were used to validate a more practical prediction method based on simplified CFD
- An innovative windshield layout able to couple top level thermal performance with high blade load reduction was identified

Closure

- Acknowledgements
  - This work was completed thanks to the support received from the European High-Performance Computing Joint Undertaking (JU)
  - Funds to complete experiment 1104 **High Performance air cooled condenser in any WIND condition (HPacC-WIND)** of the FF4EuroHPC initiative

- Next steps
  - Analyze the effect of wind gusts

WIND

HPacC-WIND
High Performance air cooled
Condenser in any WIND condition

Via G. Campani 50, 50127 Firenze

Tel - (+39) 055 5391855

Web - www.ergonresearch.it

Email - info@ergonresearch.it

P.IVA - C.F. 05877940485