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COMBINED WIND TURBINE DESIGN AND WIND FARM LAYOUT OPTIMISATION UNDER WIND RESOURCE UNCERTAINTY

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CONTENTS

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STUDY OBJECTIVES

- Combined optimisation of wind turbine design and wind farm layout
- Optimise turbine rotor diameter
- Optimise number & position of turbines for a given farm area
- Optimise orientation of turbines in the farm
- Optimisation objective: Minimise LCoE, & use uncertainty in wind resource
- Objective function: TNO Wind Cost Model

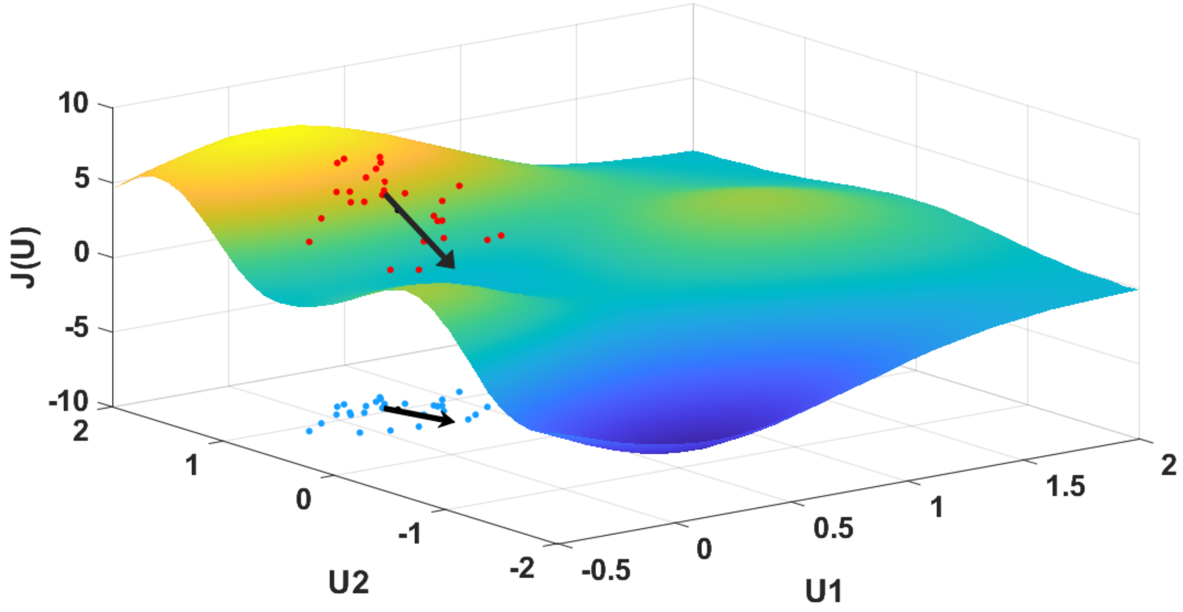
OPTIMISER

STOCHASTIC SIMPLEX APPROXIMATE GRADIENT (STOSAG)

- Developed for geological uncertainties for O&G reservoir simulations

Example with two dimensional controls:

- Choose an initial set of control variables $(u_1, u_2) = (0.25, 1)$
- Perturbation of control vectors stochastically (blue dots)
- Evaluate each perturbed control (red dots)
- Estimate the gradient using linear regression
- Update control variables using line search
- Repeat until convergence.



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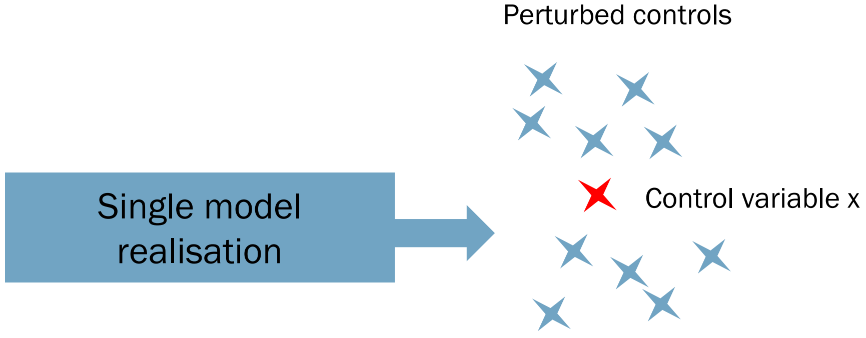
STOSAG METHOD

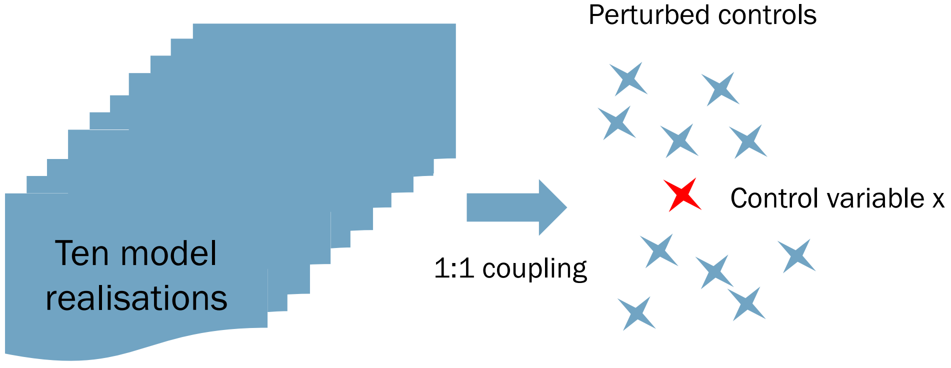
DETERMINISTIC OPTIMISATION

- No uncertainty, i.e. single model realisation
- Number of perturbed controls: 10 (for example)
- Ratio between model realisations and perturbed controls: 1:10

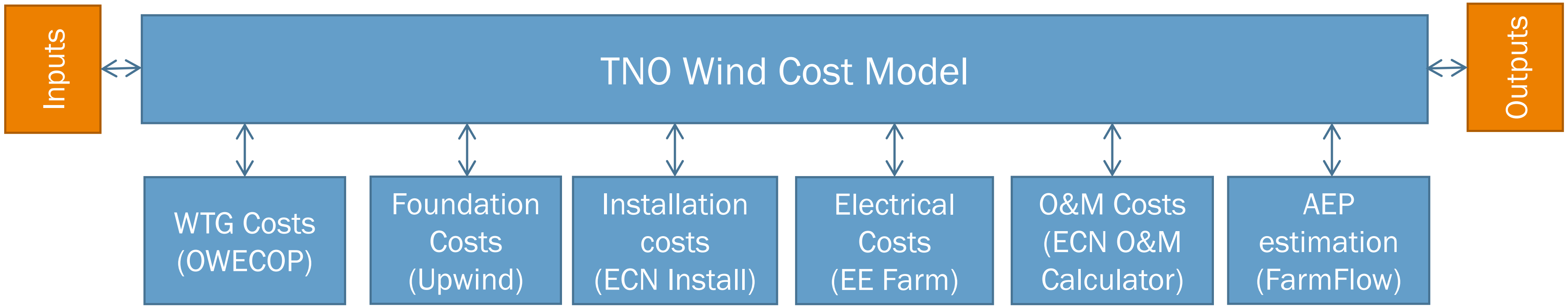


ROBUST OPTIMISATION

- 10 uncertain model realisations
- Number of perturbed controls: 10 (as above)
- One model realisation coupled with one perturbed control
- Same computational effort as deterministic case



OBJECTIVE FUNCTION



Outputs: Breakdown CAPEX, OPEX, LCOE, NPV, IRR, ROI, YTR

TNO Wind cost model used for economic evaluation of a “traditional” wind farm:

- Wind turbine with single rotor
- Monopile support structure
- Wind farm in a parallelogram shape (length, width, orientation)
- Installation and maintenance with SOVs and/or CTVs

$$LCoE = \frac{\left(\frac{CapEx}{a} + OpEx\right)}{AEP}$$

CONTROL VARIABLES

ROTOR POWER DENSITY (RPD)

- Unit: W/m^2
- Inversely proportional to square of turbine diameter (d)
- Turbine rated power fixed (10 MW AVATAR research turbine)

$$RPD = (P_{turbine})/((\pi/4)d^2)$$

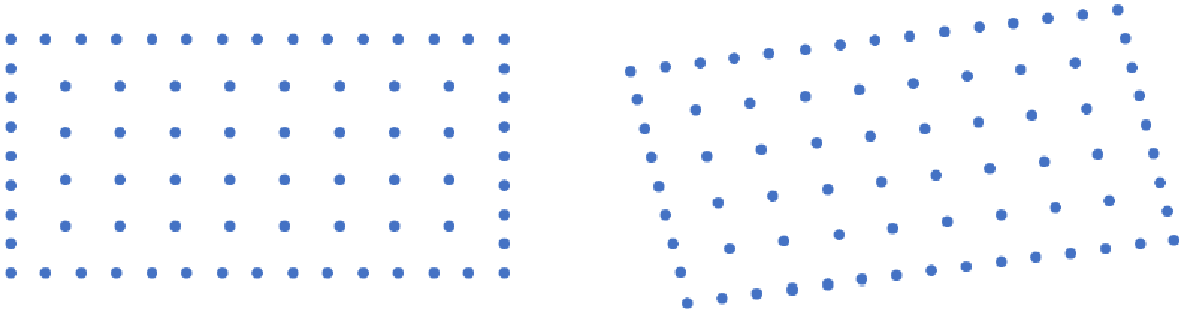
WIND FARM POWER DENSITY (WFPD)

- Unit: MW/km^2
- Directly proportional to number of turbines in farm
- Fixed farm area (150 km^2)

$$WFPD = (P_{turbine} * n_{turbines})/A_{farm}$$

FARM ORIENTATION (Θ)

- Counter clockwise rotation of turbines in the farm



UNCERTAINTY IN WIND RESOURCE

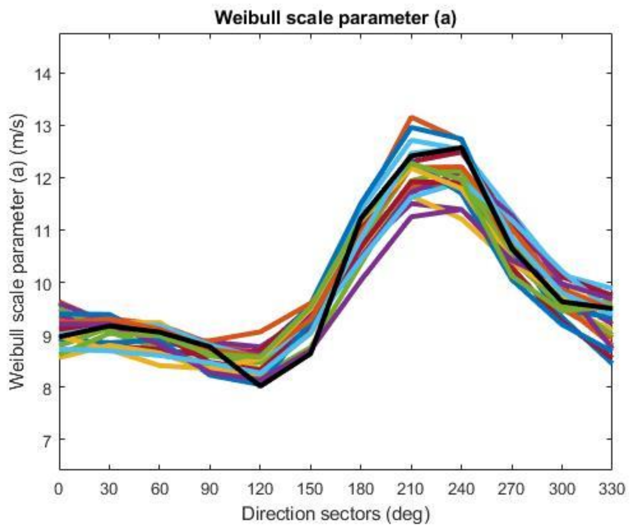
Location:

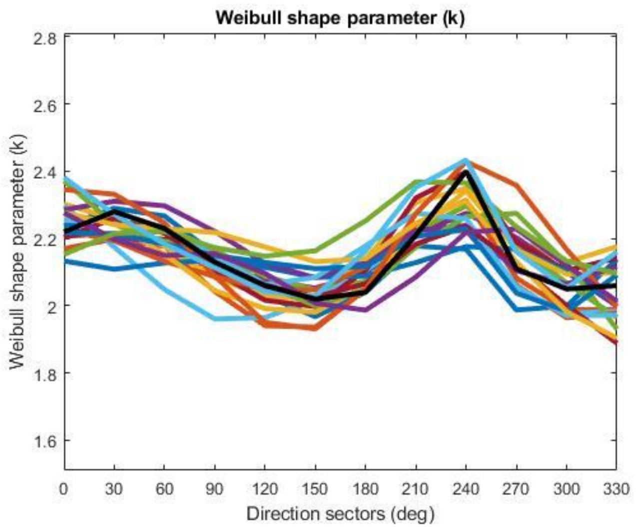
- 100m at Borssele Wind farm zone (WFS III)
- Weibull probability density function:

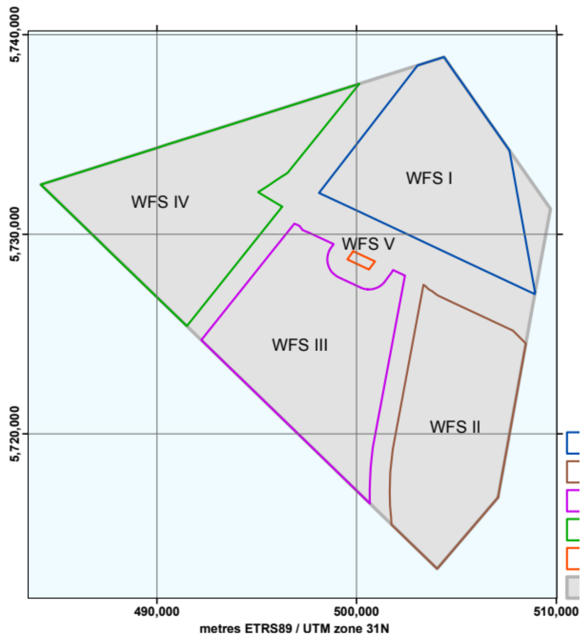
$$p(U) = \ (k/a)\left(\frac{U}{a}\right)^{k-1} \ exp\left[-\left(\frac{U}{a}\right)^{k}\right]$$

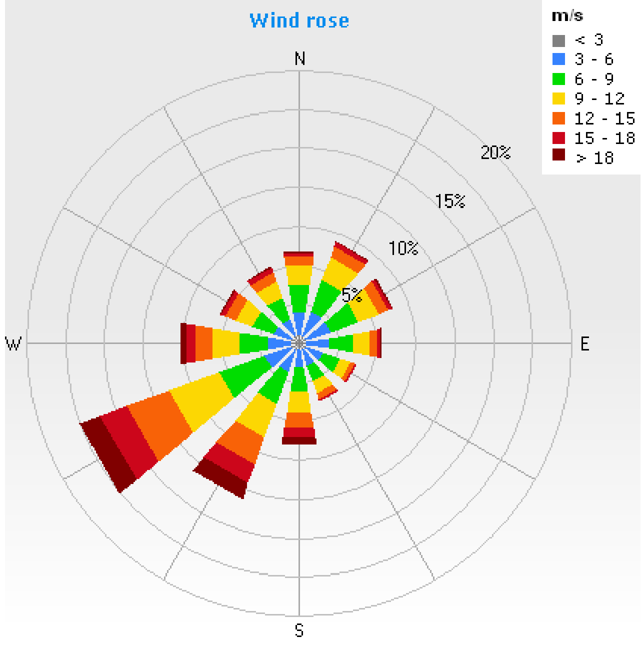
where scale parameter is (a) and shape parameter is (k)

- 5% uncertainty in Weibull a and k parameters and in each direction sector





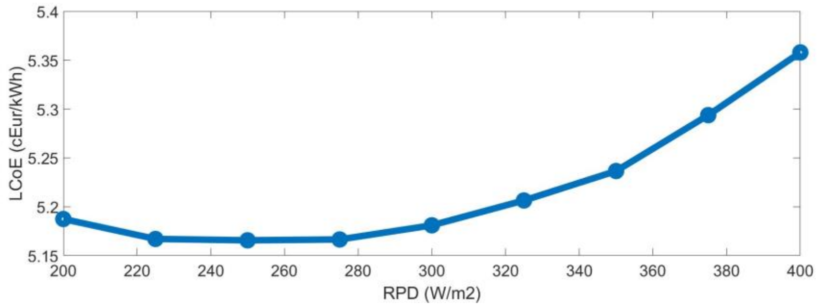


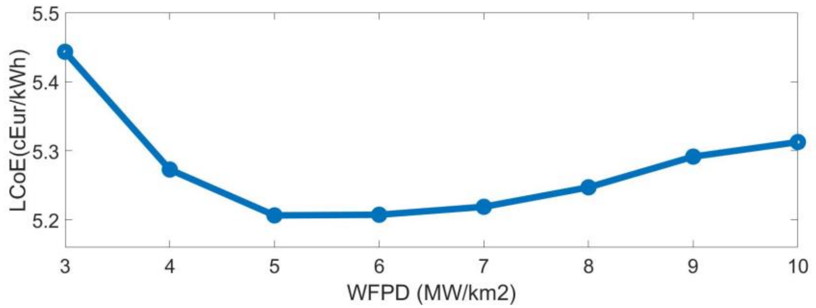


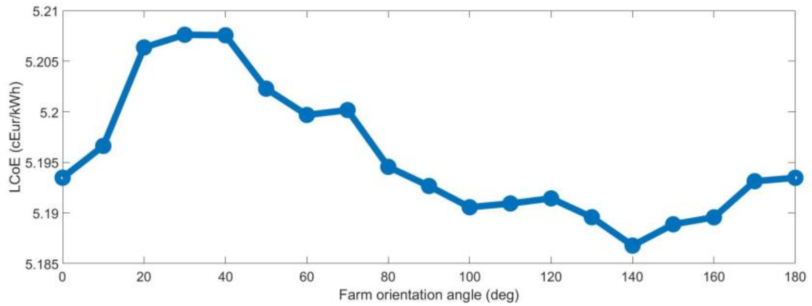
MODELLING

SENSITIVITY ANALYSIS FOR LOWEST LCOE

- Min. LCoE of ~5.15 c€/kWh
- @(RPD, WFPD, theta) = (250, 5, 140)







INITIAL CONTROL VARIABLES

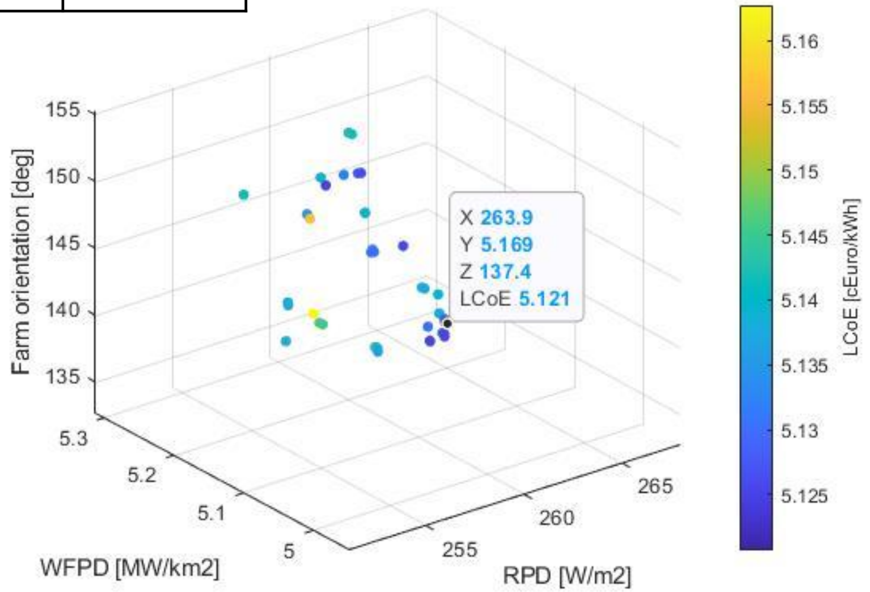
Type	Control variables	RPD (W/m^2)	WFPD (MW/km^2)	Farm angle (°)	Rotor diameter (m)	# turbines	LCoE (c€/kWh)
Deterministic, Robust	2,3	250	5	140	225.7	75	5.144, 5.152

RESULTS

DETERMINISTIC EXPERIMENTS

Type	Control variables	RPD (W/m²)	WFPD (MW/km²)	Farm angle (°)	Rotor diameter (m)	# turbines	LCoE (c€/kWh)	% decr. in LCoE
Deterministic	2	265.5	5.178	140	219.0	78	5.125	0.37%
Deterministic	3	263.9	5.171	137.4	219.7	78	5.121	0.45%

- Farm angle as third control variable decreases LCoE to 0.45%
- Optimised farm angle (137.4°) gives scope to slightly increase rotor diameter
- Rotor diameter increased by 0.7m to capture more wind



RESULTS

ROBUST EXPERIMENTS

Type	Control variables	RPD (W/m^2)	WFPD (MW/km^2)	Farm angle (°)	Rotor diameter (m)	# turbines	Mean LCoE (c€/kWh)	% decr. in mean LCoE
Robust	2	265.1	5.167	140	219.2	78	5.129	0.46%
Robust	3	264.1	5.169	131.9	219.6	78	5.128	0.47%

- With 2 control variables, 0.46% decrease in mean LCoE
- Twenty realisations cumulatively orient the wind slightly southwards
- With 3 control variables, turbine diameter slightly increases

CONCLUSIONS

- Optimise turbine design and farm layout
- Optimised design from deterministic experiments show decrease in LCoE of 0.45%
- Input uncertainty of 5% in W_a and W_k is reflected with 20 wind resource realisations
- Robust experiments, with uncertainty, reduce mean LCoE by 0.47%

FURTHER WORK

- NPV as optimisation objective, with energy integrated market model
- Estimate uncertainty from historical data by fitting distributions to W_a and W_k
- Multi-objective optimisation with LCoE and LCA (economic and environmental impact)


THANK YOU FOR
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