Optimising availability through time-domain numerical analysis

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Overview of presentation

- Background
- Integrated cost revenue model
- O&M module
- Case study and sensitivity analysis
- Indicative results
- Conclusions

Features of a high fidelity cost/revenue model

- A high-fidelity model should predict the different costs of a typical OW farm in a lifecycle-phase-sequence pattern, by:
  - adopting the most up-to-date parametric equations found in the literature;
  - developing new parametric equations where latest data are available;
  - accurately predicting operation and maintenance costs in conjunction with latest reliability data through appropriate engineering models;
  - Considering the real time of money through accounting for the time that expenses and revenues have occurred;
  - considering uncertainty of key variables in a systematic way and assigning confidence levels on the expressions of estimated KPIs.

Model	Institution/Owner	Year	Commercial	Software	Model output	Ref
os *et al*	CENTEC, Univ. of Lisbon (Portugal)	2018	No	GRIF (Petri Net)	Costs, Availability	[38]
O&M ss	ECN	2017	Yes	Not specified	Accessibility	[39], [40]
di *et al*	Univ. of Exeter (UK)	2017	No	Not specified	Costs, Availability	[41]
ihl and nsen	Alborg Univ. (Denmark)	2017	No	Not specified	Cost, Availability RCM	[42]
al	Universities of Playmouth, Stirling, Liverpool (UK), and Le Havre (France)	2016	No	Xpress IVE	Costs, Optimal maintenance	[43]
nko *et al*	Univ. of Hamburg, Bremen Univ. of Applied Sciences (Germany)	2015	No	BPMN 2.0, DESMO-J (Java)	Costs	[44], [45]
erud *et al*	Univ. of Stavanger (Norway)	2014	No	AnyLogic (Java)	Costs Availability	[46]
lcob	NOWITECH	2013		Not specified	Costs Availability	[36]
oodie *et al*	Univ. of Strathclyde (UK)	2013	No	MATLAB	Costs Availability	[47]
et al	Univ. of Michigan (USA)	2010	No	DESJAVA	Costs Availability	[48]
s	DNV	2010	Yes	Not specified	Net present value	[49]
OX	Systecon	2010	Yes	Not specified	Costs Optimal maintenance	[50]
rola tool	Iberdrola	2010	Yes	Not specified	CAPEX/OPEX Power	[51]
OST	BMT	2009	Yes	Not specified	Net present value	[51]
E	ECN	2009	Yes	MATLAB	Costs	[52], [53]
ard *et al*	KTH Chalmers (Sweden)	2009	No	GAMS, MATLAB	Costs	[54], [55]
el- rez and nsen	Alborg Univ. (Denmark)	2008	No	Not specified	Costs	[56], [57]
	GL Garrad Hassan (DNV)	2007	Yes	Not specified	Costs Lost production	[37]
O&M	ECN	2007	Yes	Excel @Risk	Costs	[35], [58], [59]
adwaj *et al*	Loughborough Univ. TWI Ltd (UK)	2007	No	Excel @Risk	Net present value	[60]
awus *et al*	Robert Gordon Univ. (UK)	2006	No	Excel, Cristal Ball	Net present value	[61]
FF-model	ECN	2004	No	Excel @Risk	Costs	[62]
ens *et al*	Universite Libre de Bruxelles (Belgium)	2004	No	GRIF (Petri Net)	Costs Availability	[63]
TOFAX	TU Delft (Netherlands)	1997	No	Excel	Costs Availability Power	[35]

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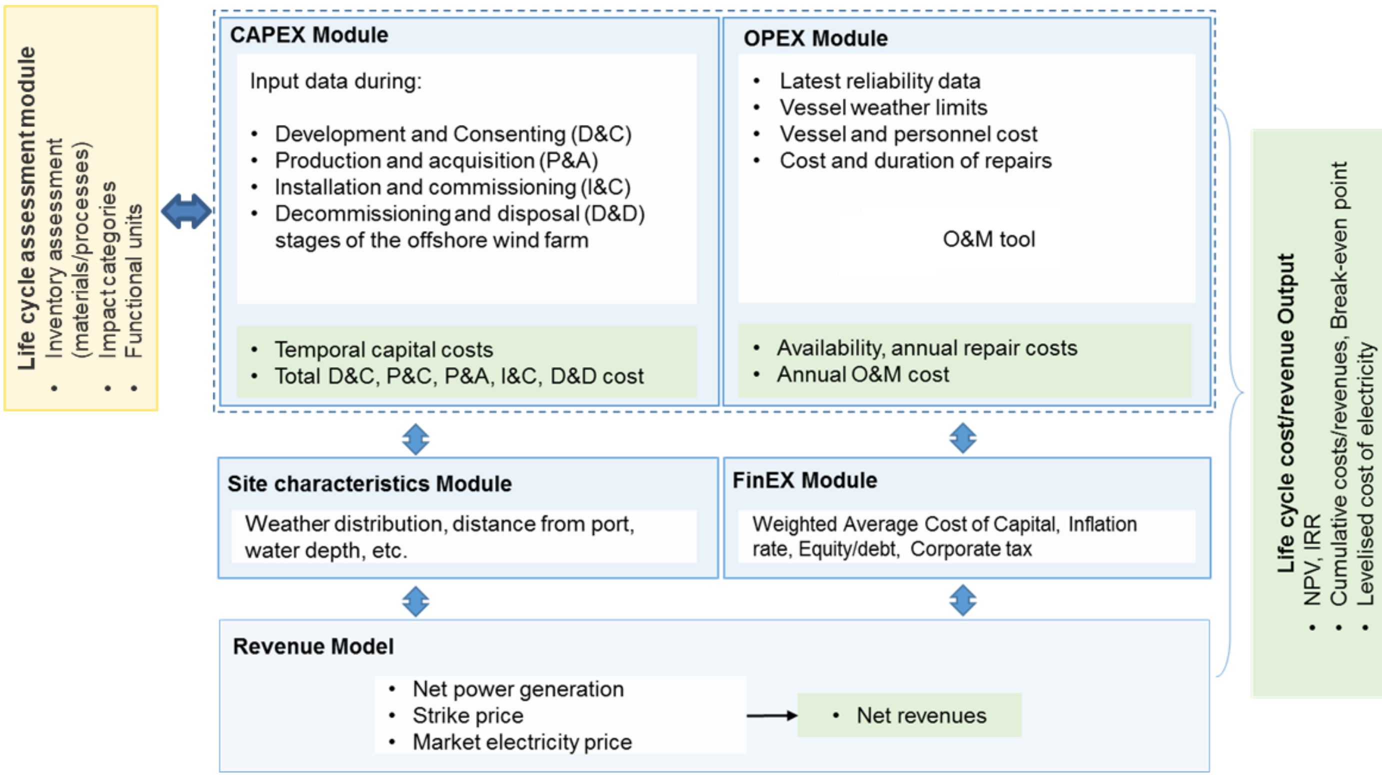
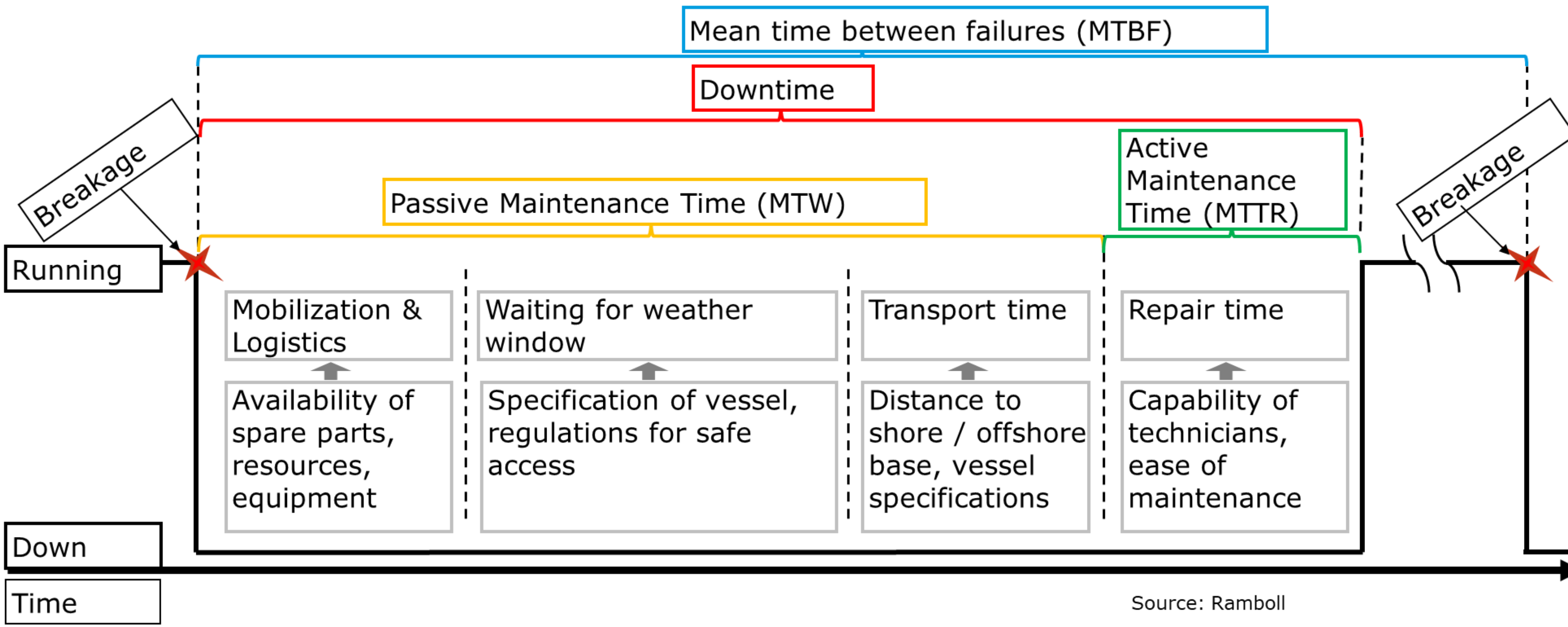
Integrated cost revenue model

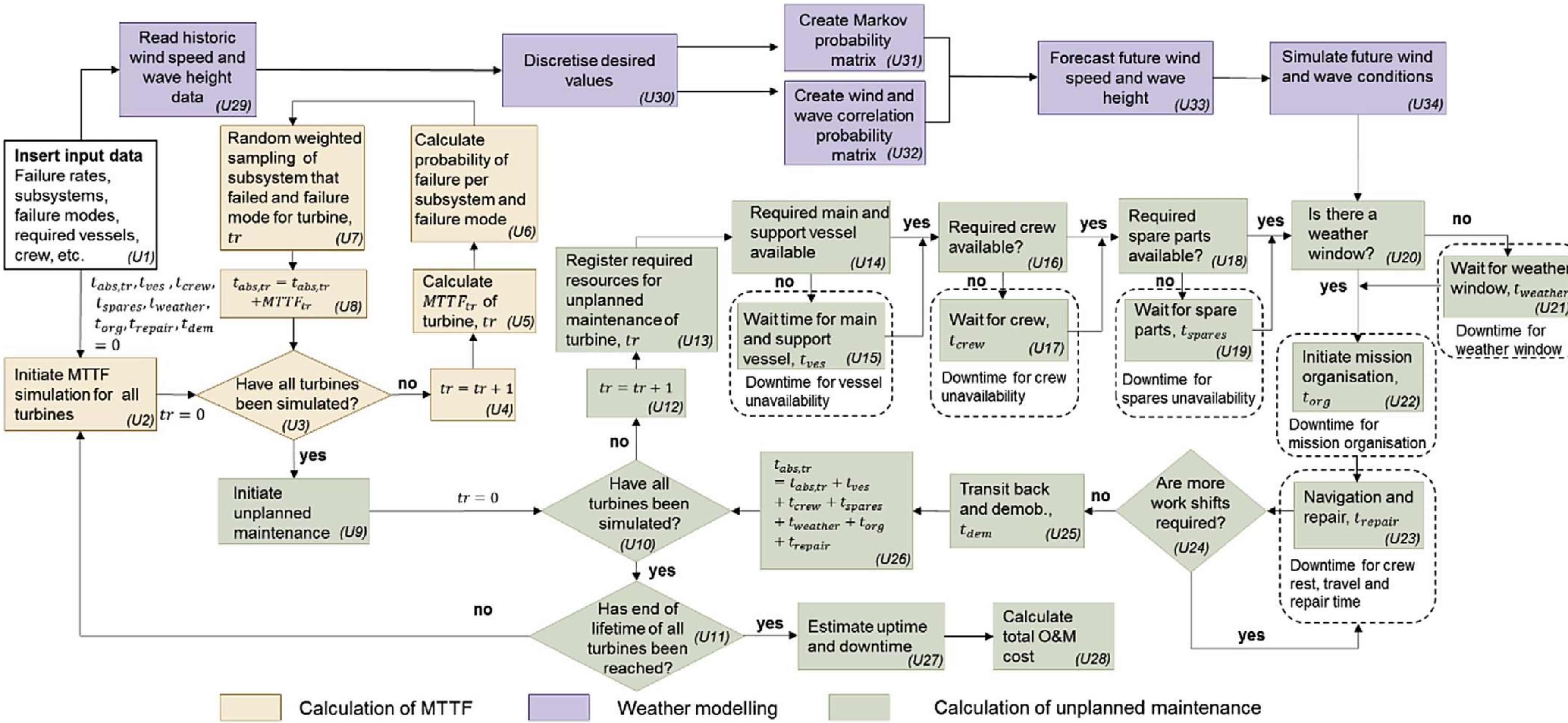


Availability basics



Source: Ramboll

O&M module



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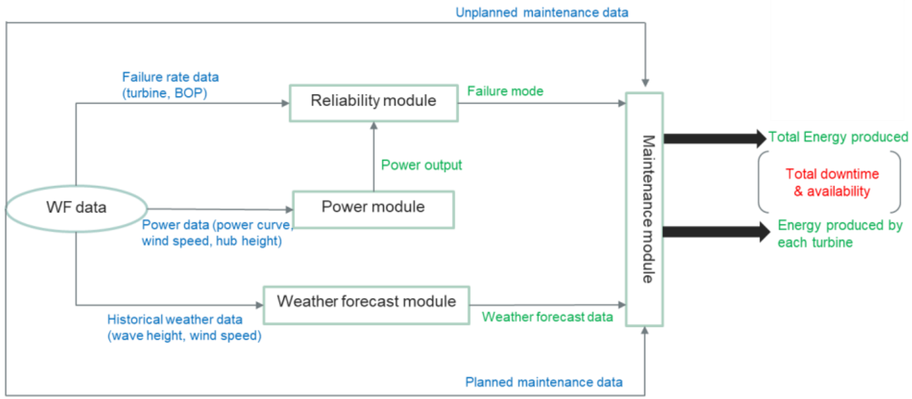
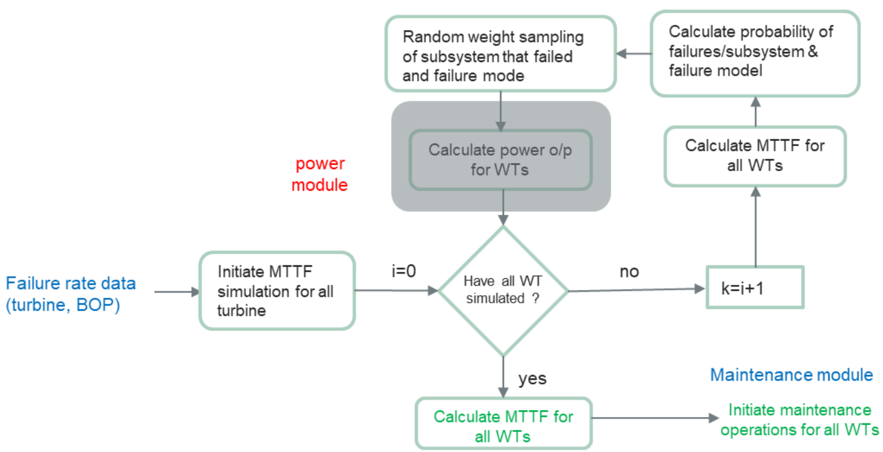
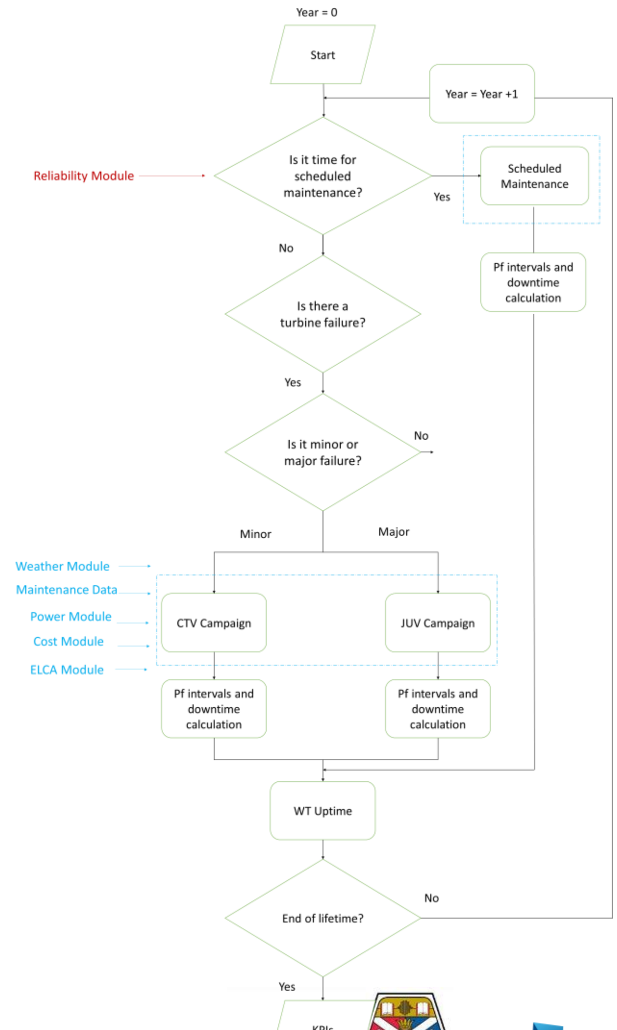
O&M module



O&M cost module framework



Reliability module framework



Maintenance module framework

Inputs for the individual modules

Module	Input
Site characteristics module	Total wind farm capacity
	Projected operational life of the wind farm
	Construction years
	Number of turbines
	Distance to port
	Water depth
	Rotor diameter
	Hub height
	Pile diameter
	Rated power
	Cut-in speed
	Cut-out speed
	Vessel information
	Personnel costs

Module	Input
FinEX module	Weight Average Cost of Capital
	Inflation rate
	Equity to debt ratio
EIA module	Greenhouse gas emissions of materials
	Masses of materials
	Vessel consumption
	Vessel speed

Inputs for the individual modules

LCC module	Legal costs
	Environmental survey costs
	Engineering costs
	Contingency costs
	Project management cost
	Unit cost of cables
	Tonnage of scour protection per unit
	Rock-dumping vessel capacity
	Number of trips required to the installation of scour protection
	Total transportation time of scour protection by rock-dumping vessel
	Dumping time per trip
	Loading time per trip and Mobilisation cost of rock-dumping vessel
	Installation rates of export and array cables
	Number of piles per substation foundation
	Rate of piling the piles of the substructure
	Depth of pile under the soil
	Reposition time of the vessel
	Installation time of the substation's jacket

O&M module	Failure rates
	Sub-system breakdown
	Failure categories
	Wind speed
	Wave height
	Energy price
	Interest rates
	Material costs
	Vessel costs
	Crew costs
	Maintenance times
	Subsystem grouping
	Required crew
	Required main vessel type
	Required support vessel type
	Repair times
	Required crew number
	Required main vessel type
	Required support vessel type
	Spare stock initial
	Spare stock minimum
	Spare wait time
	Mission organization time

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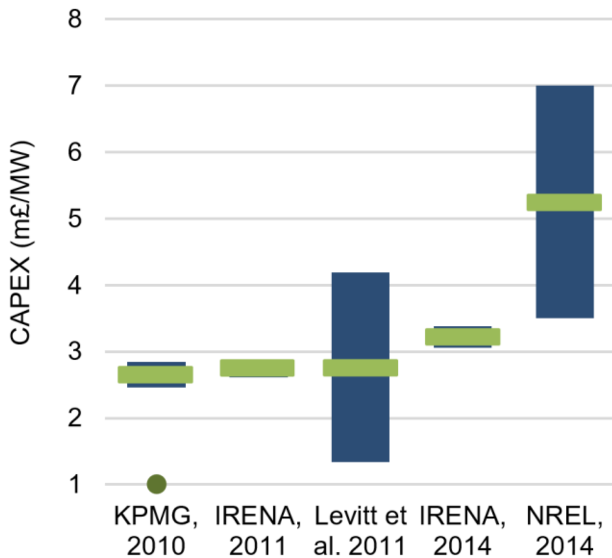
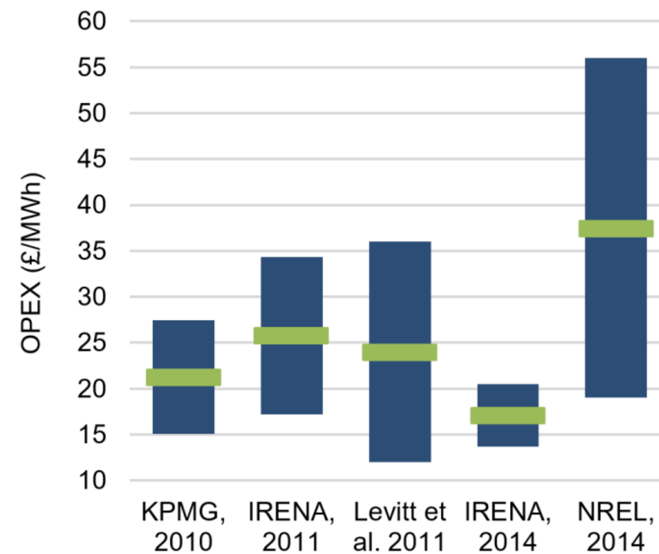
Uncertainty in cost data



Range and average values of capital costs (£m/MW) in existing literature compiled and converted to 2015 £ currency (Sources: [1]–[5])



Range values of operating costs (£/MWh) in existing literature compiled and converted to 2015 £ currency (Sources: [1]–[5])

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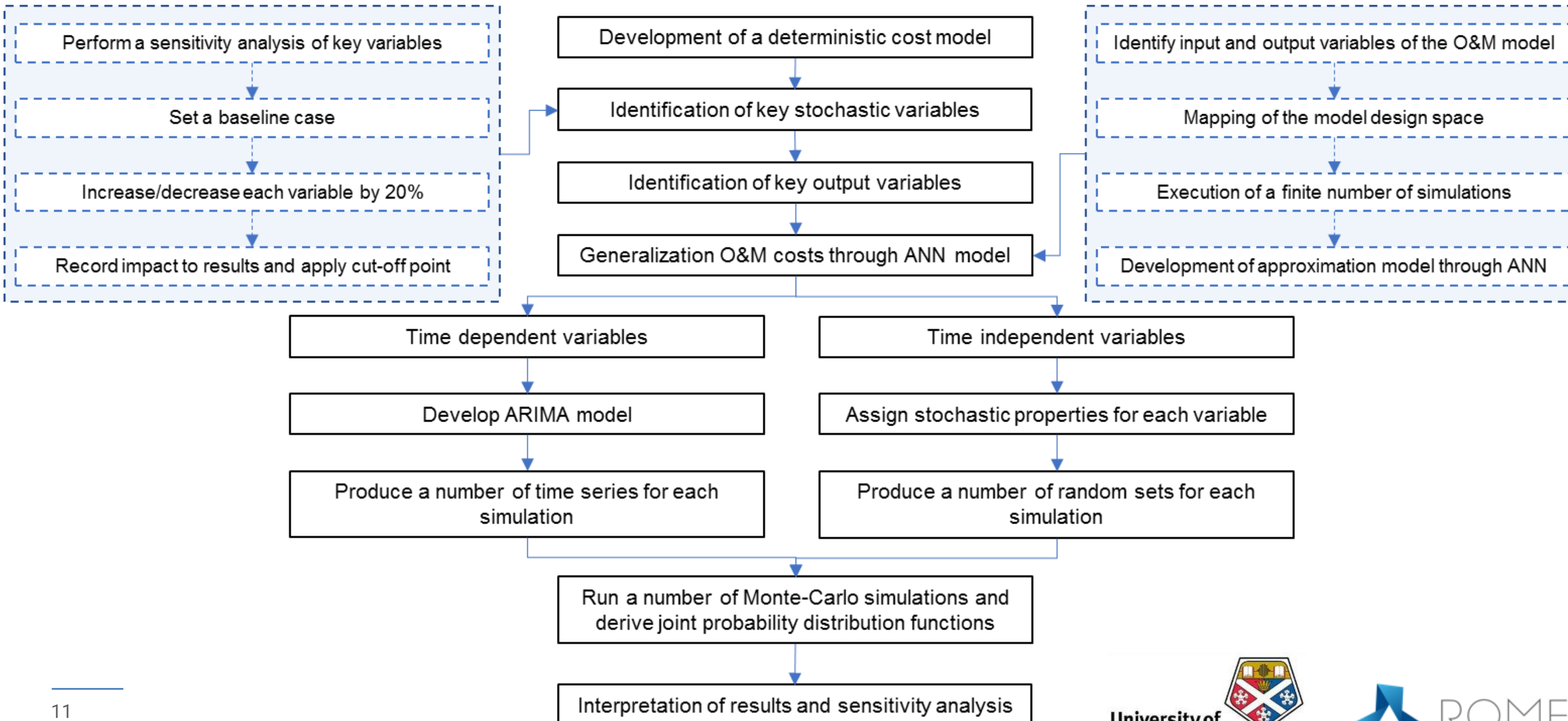
Stochastic expansion of cost revenue model



Case study: 504 MW offshore wind farm

Wind farm

- Total wind farm capacity, P_{WT}=504MW
- Projected operational life of the wind farm,n=25years
- Construction years, T_{constr}=5years
- Number of turbines, n_{WT}=140

Site characteristics

- Distance to port, D=36km
- Water depth, WD=26m

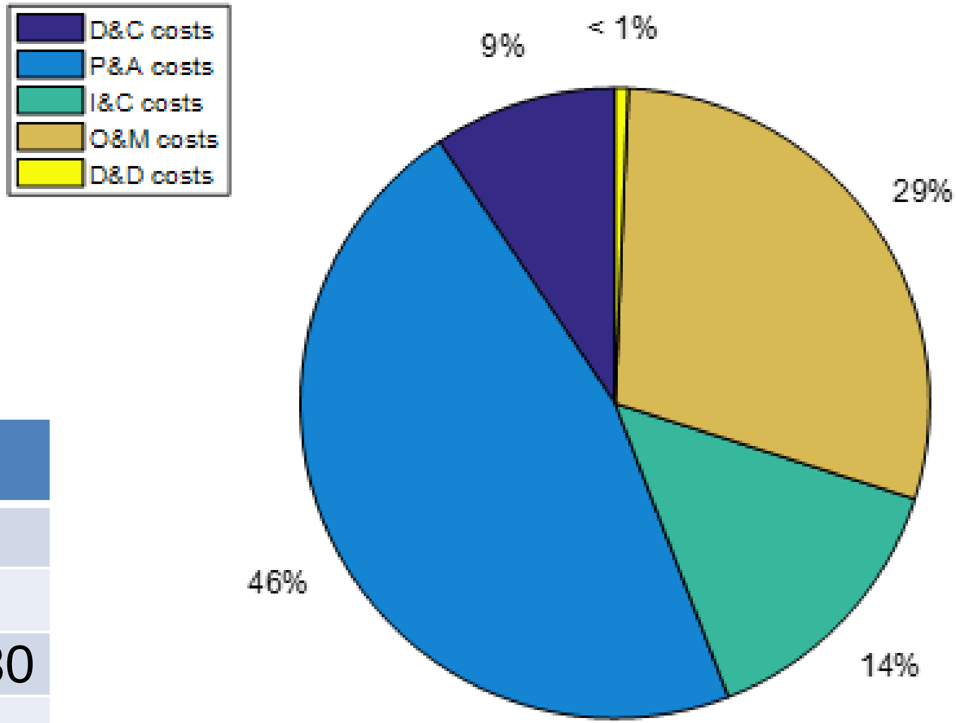
Wind turbine

- Rotor diameter, d=107m
- Hub height, h=77.5m
- Pile diameter, D_{pile}=6m
- Rated power: 3.60MW
- Cut-in speed:4m/s
- Cut-out speed: 25m/s

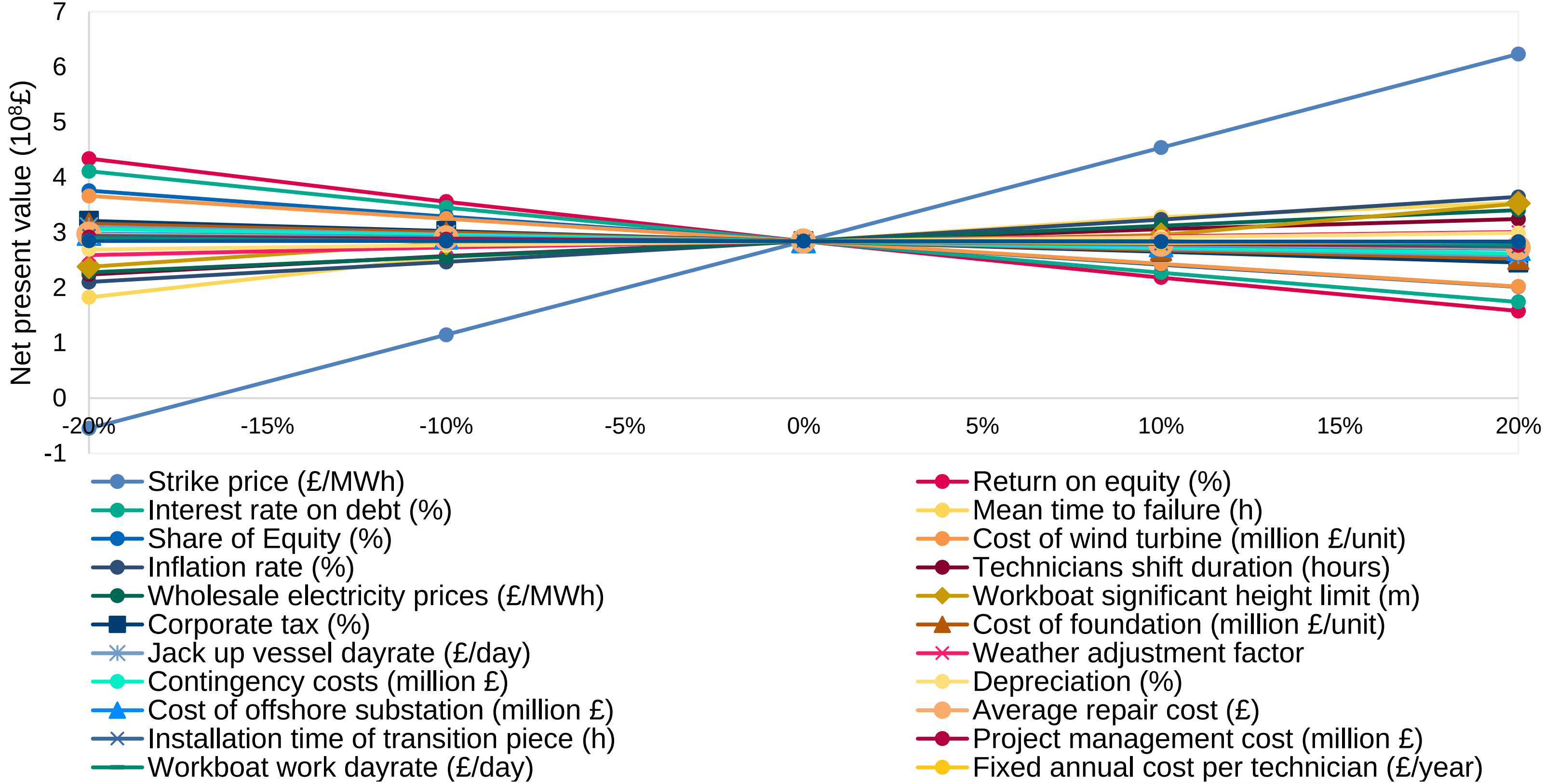
Case study: Life cycle cost breakdown

- CAPEX = £1.674 billion (Total undiscounted)
- Annual OPEX = £56.597 million
- NPV = £284 million at a real discount rate of 6.15% with an IRR= 10.3%
- LCOE= 109 £/MWh

Lifecycle costs	Value
CAPEX in k£	
Total P&C costs, $C_{P\&C}$	205,750
Total P&A costs, $C_{P\&A}$	1,040,230
Total I&C costs, $C_{I\&C}$	305,742
Total D&D costs, $C_{D\&D}$	122,860
OPEX in k£/year	
Total O&M costs, $C_{O\&M}$	56,597



Case study: Sensitivity analysis



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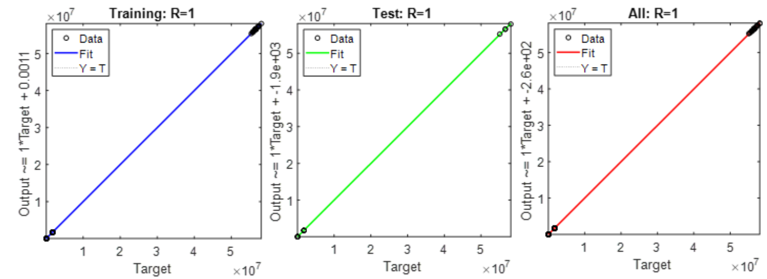
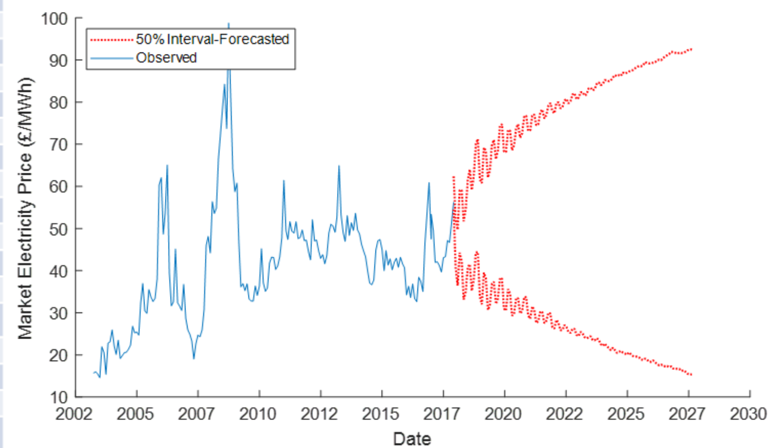
Stochastic inputs/Approximation models

Variable	Type of distribution	Characteristic values
CAPEX parameters		
Cost of wind turbine (million £/unit)	Uniform	Min: 2.85, Max: 3.37
Cost of foundation (million £/unit)	Uniform	Min: 1.14, Max: 2.77
Technicians shift duration (hours)	Normal	μ= 11, σ=1.1
Weather adjustment factor	Normal	μ= 0.85, σ=0.085
Contingency costs (million £)	Normal	μ=126.4, σ=12.6
Cost of offshore substation (million £)	Normal	μ= 29.5, σ=2.95
OPEX parameters		
Average repair cost (£)	Normal	μ= 1, σ=0.1
Mean time to failure (h)	Normal	μ= 1, σ=0.1
Revenue parameters		
Strike price (£/MWh)	3 Scenarios	
Wholesale electricity prices (£/MWh)	ARIMA	
FINEX parameters		
Share of Equity (%)	Normal	μ= 30.00%, σ=3.00%
Inflation rate (%)	Normal	μ= 2.50%, σ=0.25%
Corporate tax (%)	Normal	μ= 17.00%, σ=1.70%
Depreciation (%)	Normal	μ=18.00%, σ=1.80%
Return on equity (%)	Normal	μ= 15.80%, σ=1.58%
Interest rate on debt (%)	Normal	μ= 7.00%, σ=0.70%
General parameters		
Workboat significant height limit (m)	Normal	μ= 1.8, σ=0.18
Workboat work dayrate (£/day)	Normal	μ= 3,250, σ=325
Jack up vessel dayrate (£/day)	Normal	μ= 112,600, σ=11,260
JUV mobilisation /demobilisation cost (£)	Normal	μ= 405,000, σ=40,500
Fixed annual cost per technician (£/year)	Normal	μ=95,000, σ=9,500





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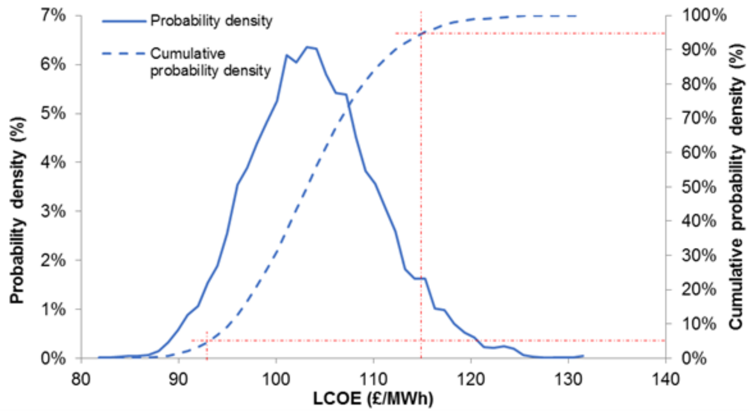
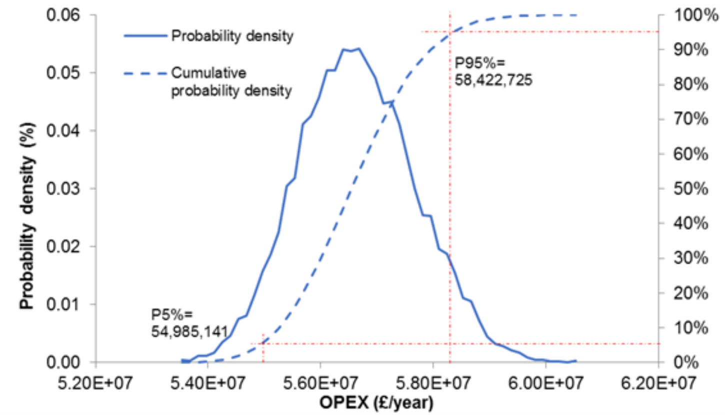
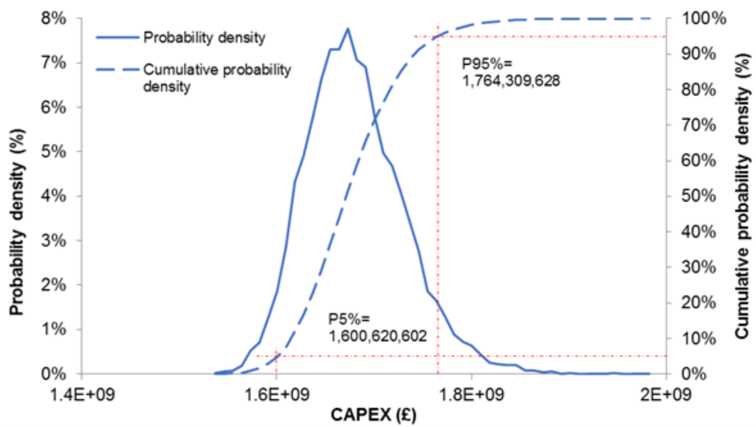
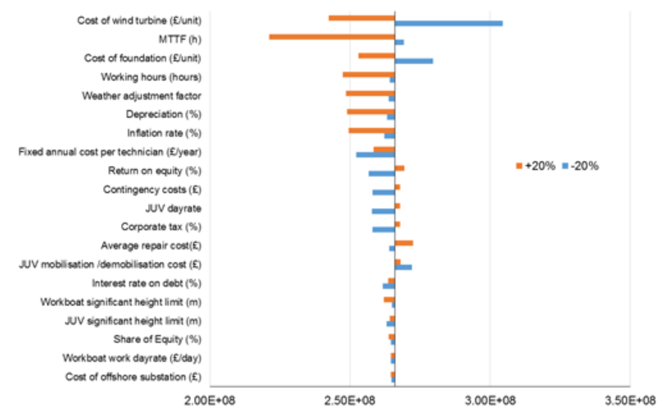
Probabilistic results

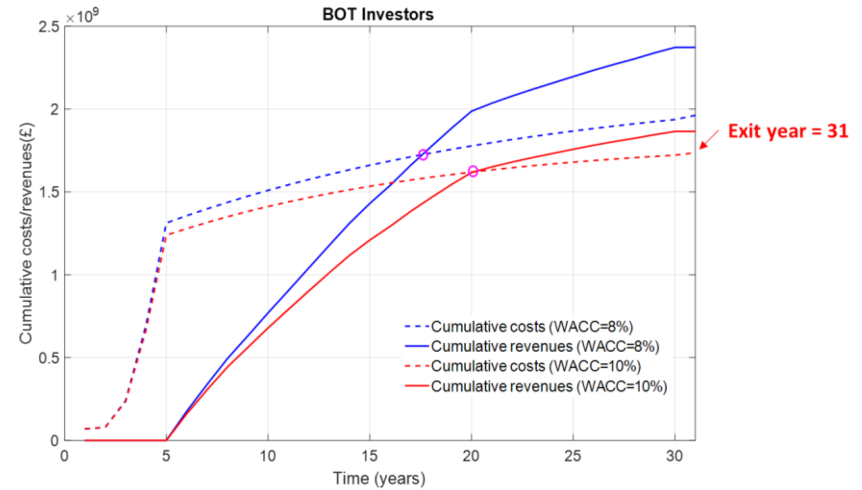


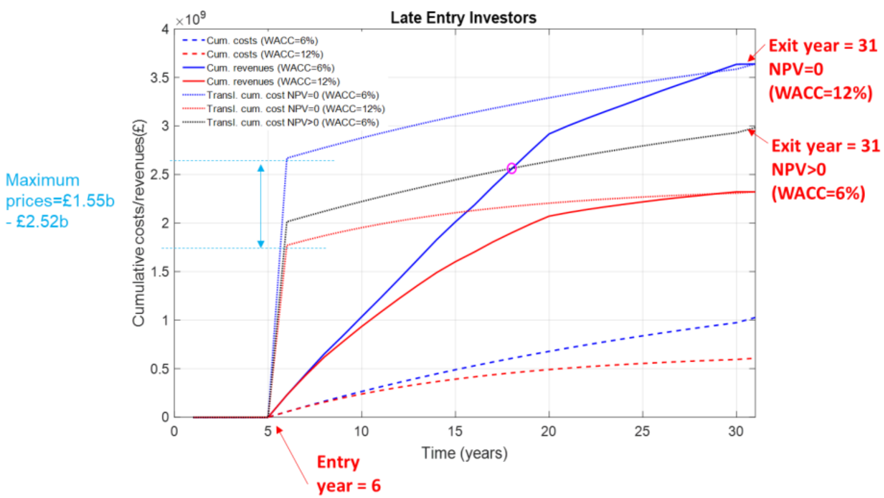


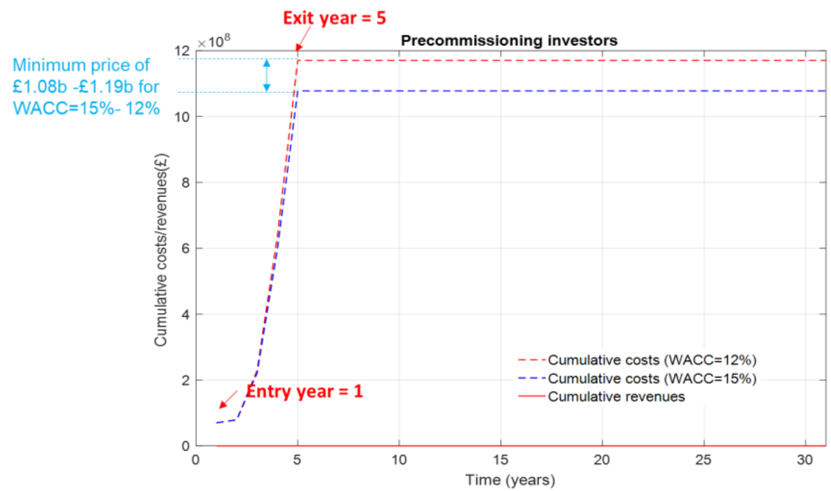




Cost/revenue profiles of different investor strategies







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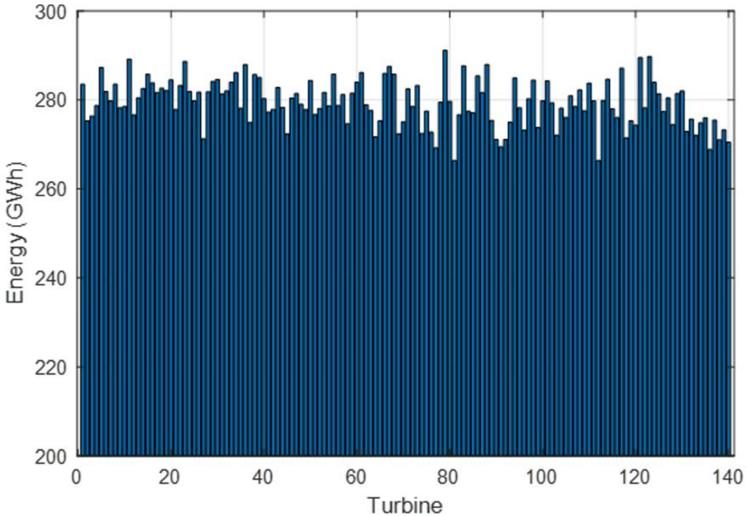
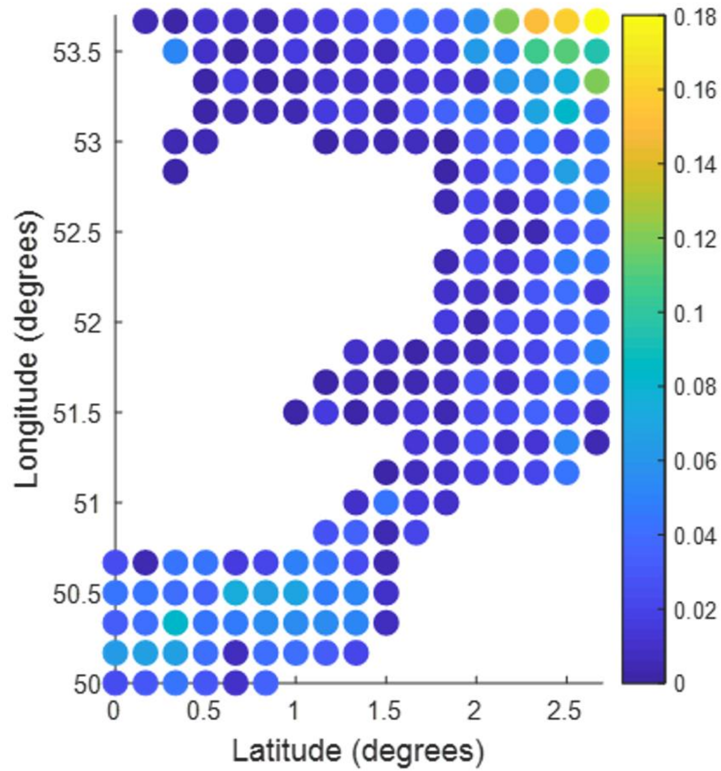
Baseline case and variation to debt to equity ratio

```
NPV =

   2.8437e+08

Return =

    0.1028

LCOE =

  108.9047

total_capex =

   1.6746e+09

total_opex =

   1.4149e+09

total_annual_opex =

   5.6597e+07

disc_capex =

   1.3026e+09

disc_opex =

   5.6158e+08

disc_capex_share =

    0.6987

disc_opex_share =

    0.3013
```

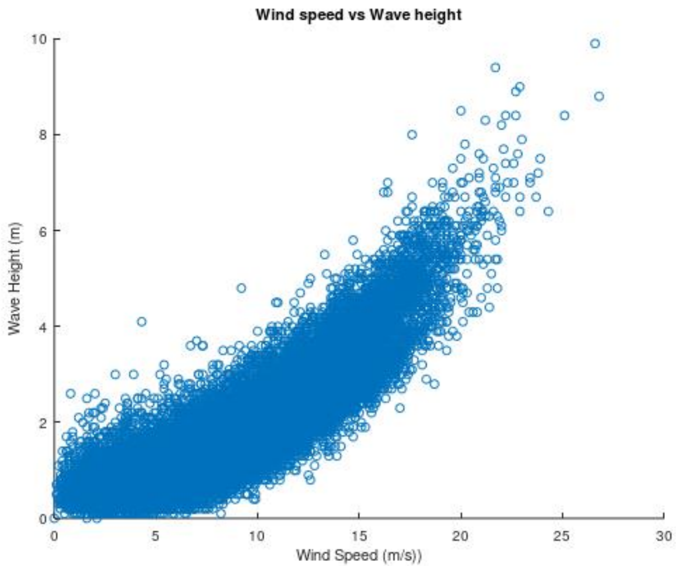
```
NPV =

   2.1501e+08

Return =

    0.1028

LCOE =

  112.6430

total_capex =

   1.6746e+09

total_opex =

   1.4149e+09

total_annual_opex =

   5.6597e+07

disc_capex =

   1.2815e+09

disc_opex =

   5.2695e+08

disc_capex_share =

    0.7086

disc_opex_share =

    0.2914
```

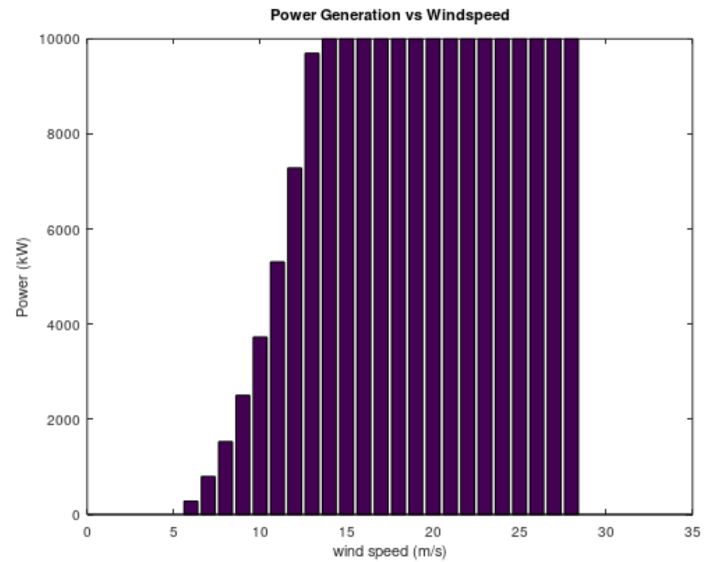
LCC module outputs





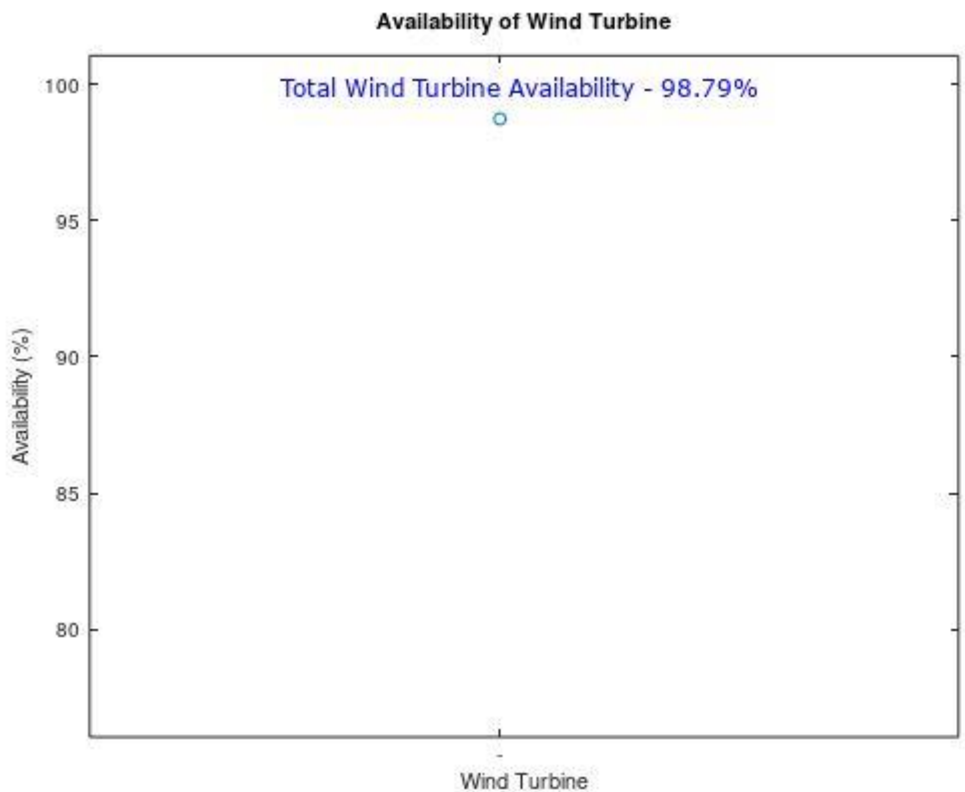
O & M Modelling Outputs – Preliminary Results





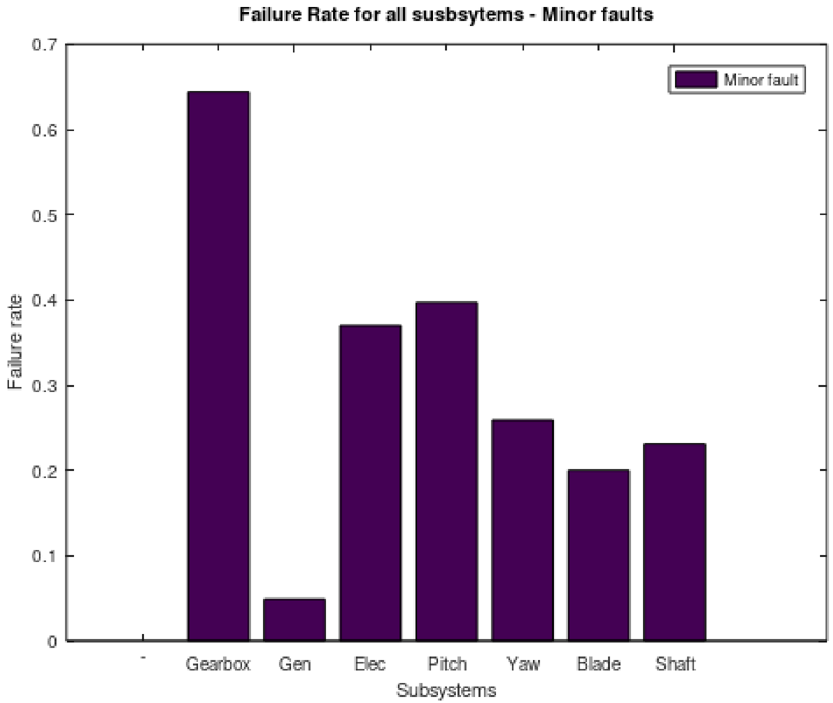
Power Module

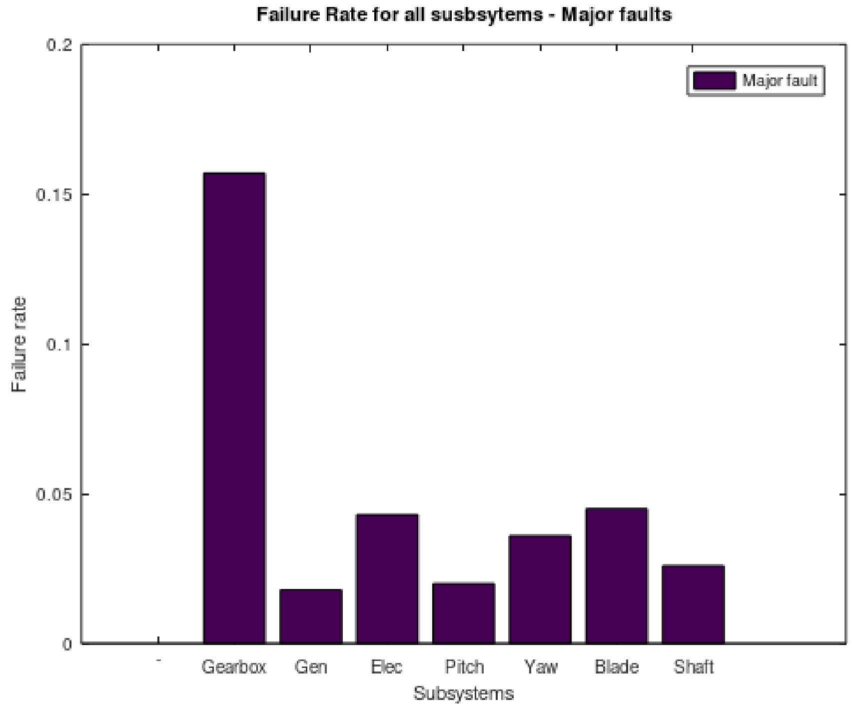
O & M Modelling Outputs – Preliminary Results



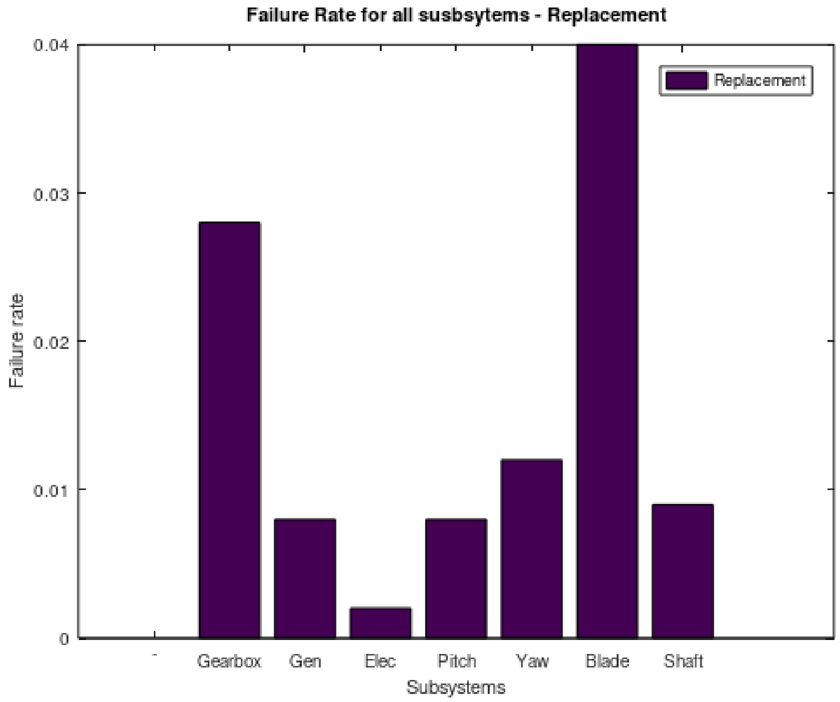
Maintenance Module

O & M Modelling Outputs – Preliminary Results



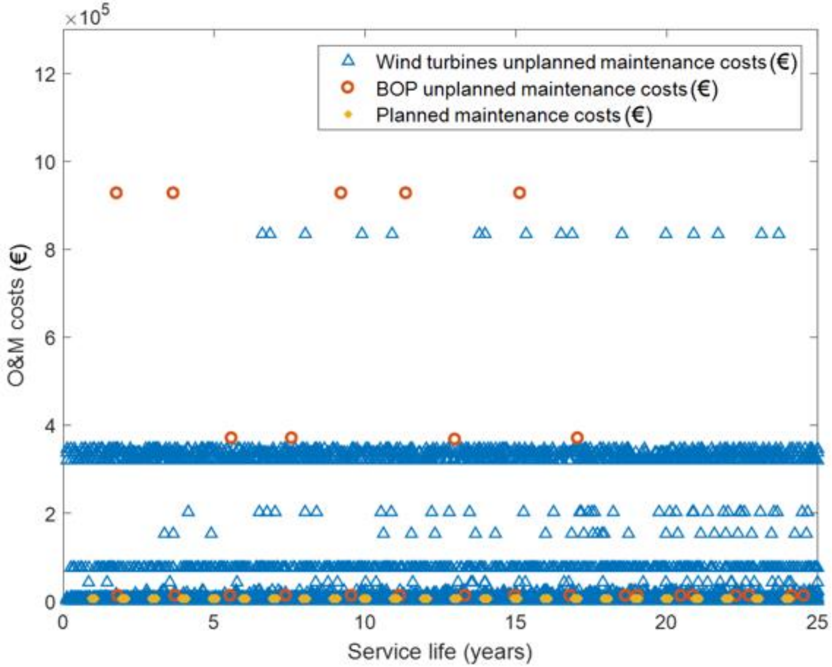


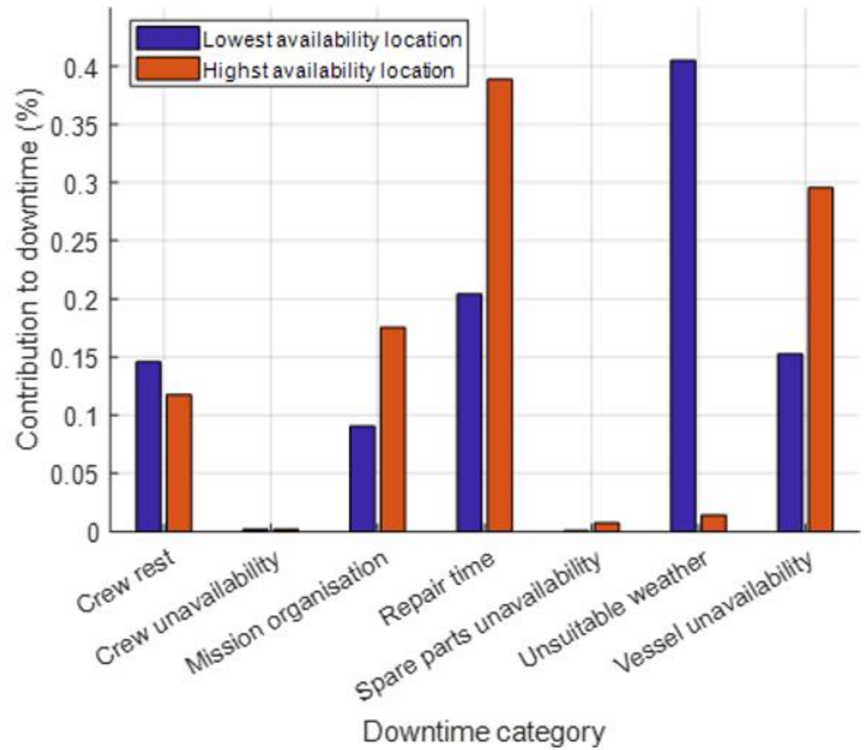
O & M Modelling Outputs – Preliminary Results



Reliability Module

O & M Modelling Outputs – Preliminary Results





Maintenance Module

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Reducing Failure rates by 30%

Iteration	Availability (%)	Energy (GWh)	Revenue (€)
1	97.89580957	32798.77671	1836558003
2	98.02712073	32577.74309	1848318127
3	97.81984063	33326.85527	1944797386
Average	97.91425698	32900.93706	1876557838

Iteration	Materials Unplanned(€)	Vessels Unplanned (€)	Mobilisation Unplanned (€)	Demobilisation Unplanned (€)	Crew Unplanned (€)	Materials Planned (€)	Vessels Planned (€)	Crew Planned (€)
1	5864164.555	128572075.3	23221179.12	0	5705634.845	1824923.263	10011007.62	2815595.892
2	5371436.554	119813022.6	23829702.29	0	5123797.152	1823185.448	10001474.46	2812914.691
3	5260505.643	130989223.1	24180388.12	0	5884868.515	1823015.869	10000544.2	2812653.055
Average	5498702.251	126458107	23743756.51	0	5571433.504	1823708.193	2813721.212	10004342.09
Unplanned costs	161271999.3							
Planned costs	14641771.49							
Total Direct Costs	175913770.8							

Reducing cost of materials by 20%

Iteration	Availability (%)	Energy (GWh)	Revenue (€)
1	96.59370603	34519.97367	2182041637
2	96.28668789	34735.04959	2179002842
3	96.10328373	35310.98592	2274202102
Average	96.32789255	34855.29819	2211748860

Iteration	Materials Unplanned(€)	Vessels Unplanned (€)	Mobilisation Unplanned (€)	Demobilisation Unplanned (€)	Crew Unplanned (€)	Materials Planned (€)	Vessels Planned (€)	Crew Planned (€)
1	7270640.32	193586375.4	29674327.61	0	8990230.212	1833073.965	10055720.04	2828171.26
2	7550710.042	196906994.9	32755568.11	0	8891074.086	1833681.863	10059054.79	2829109.16
3	6370903.946	174975704.9	26806993.37	0	8495878.186	1831073.908	10044748.3	2825085.458
Average	7064084.769	188489691.8	29745629.7	0	8792394.161	1832609.912	2827455.293	10053174.37
Unplanned costs	234091800.4							
Planned costs	14713239.58							
Total Direct Costs	248805040							

Increasing PF intervals by 100%

Iteration	Availability (%)	Energy (GWh)	Revenue (€)
1	97.05090104	51588.96295	3068392492
2	96.70629713	51982.78137	3052842265
3	96.45136688	52328.60332	3122377093
Average	96.73618835	51966.74433	3081203950

Iteration	Materials Unplanned(€)	Vessels Unplanned (€)	Mobilisation Unplanned (€)	Demobilisation Unplanned (€)	Crew Unplanned (€)	Materials Planned (€)	Vessels Planned (€)	Crew Planned (€)
1	9088300.4	193586375.4	29674327.61	0	8990230.212	1833073.965	10055720.04	2828171.26
2	9438387.552	196906994.9	32755568.11	0	8891074.086	1833681.863	10059054.79	2829109.16
3	7963629.933	174975704.9	26806993.37	0	8495878.186	1831073.908	10044748.3	2825085.458
Average	8830105.961	188489691.8	29745629.7	0	8792394.161	1832609.912	2827455.293	10053174.37
Unplanned costs	235857821.6							
Planned costs	14713239.58							
Total Direct Costs	250571061.2							

Extend service life to 40 yrs

Iteration	Availability (%)	Energy (GWh)	Revenue (€)
1	96.23777013	57047.0823	2851794736
2	95.86665208	56557.78095	2809534434
3	95.88835345	57068.16443	2796246078
Average	95.99759189	56890.90065	2819191750

Iteration	Materials Unplanned(€)	Vessels Unplanned (€)	Mobilisation Unplanned (€)	Demobilisation Unplanned (€)	Crew Unplanned (€)	Materials Planned (€)	Vessels Planned (€)	Crew Planned (€)
1	11558628.62	229696825.4	37231929.98	0	11522052.56	1382480.043	7583890.52	2132969.209
2	12297363.92	275305692.3	40166387.63	0	12019255.37	1382024.782	7581393.092	2132266.807
3	12649649.34	288751552.8	41945712.15	0	13124171.43	1383607.522	7590075.547	2134708.747
Average	12168547.29	264584690.2	39781343.26	0	12221826.45	1382704.116	2133314.921	7585119.72
Unplanned costs	328756407.2							
Planned costs	11101138.76							
Total Direct Costs	339857545.9							

Reduction of distance to 25%

Iteration	Availability (%)	Energy (GWh)	Revenue (€)
1	96.59370603	34519.97367	2182041637
2	96.28668789	34735.04959	2179002842
3	96.10328373	35310.98592	2274202102
Average	96.32789255	34855.29819	2211748860

Iteration	Materials Unplanned(€)	Vessels Unplanned (€)	Mobilisation Unplanned (€)	Demobilisation Unplanned (€)	Crew Unplanned (€)	Materials Planned (€)	Vessels Planned (€)	Crew Planned (€)
1	9088300.4	193586375.4	29674327.61	0	8990230.212	1833073.965	10055720.04	2828171.26
2	9438387.552	196906994.9	32755568.11	0	8891074.086	1833681.863	10059054.79	2829109.16
3	7963629.933	174975704.9	26806993.37	0	8495878.186	1831073.908	10044748.3	2825085.458
Average	8830105.961	188489691.8	29745629.7	0	8792394.161	1832609.912	2827455.293	10053174.37
Unplanned costs	235857821.6							
Planned costs	14713239.58							
Total Direct Costs	250571061.2							

Impact assessment scenarios and KPIs

1. How much do KPIs change if we reduce unplanned maintenance by 60/80% (related to SO5)?
2. How much do KPIs change if we invest in CMS and obtain PF intervals by 30% of TTF?
3. How much do KPIs change if we achieve reduction in failure rates by 30% (related to SO1)?
4. How much do KPIs change if we achieve reduction in material costs by 16% (related to SO4)?
5. How much do KPIs change if we assume life extension by 5/10/20 years?
6. How much do KPIs change if we invest in CMS and reduce inspections by 30% (related to SO3)?
7. How much do KPIs change if we invest in CMS and reduce inspections by 24-47% specifically for jacket substructures (related to SO6)?
8. How much do KPIs change if we reduce cost of jacket substructures by 19-41% (related to SO7)?
9. How much do KPIs change if we reduce overall O&M costs by 8% across the offshore wind farm (related to SO8)?
10. How much do KPIs change if we adjust maintenance strategy dynamically, instead of considering a constant through-life strategy?

Wind turbine availability	Wind farm availability
Maintenance cost	OPEX
LCoE	NPV
Revenue loss	Downtime
Duration of offshore operations	Environmental Impact

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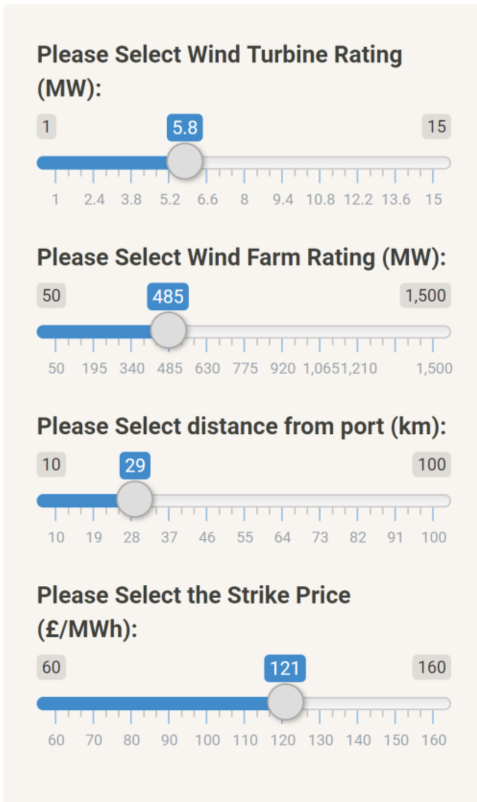
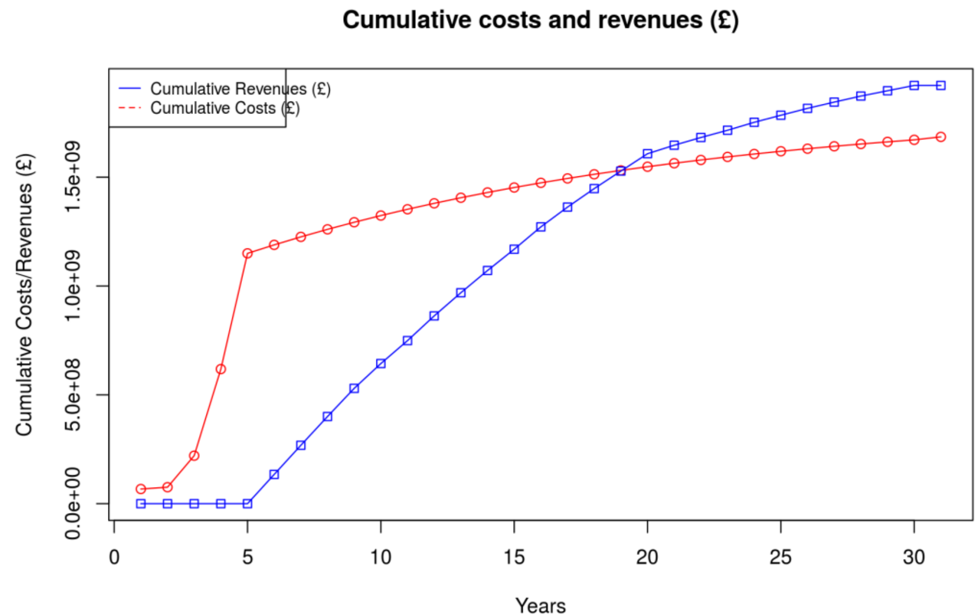
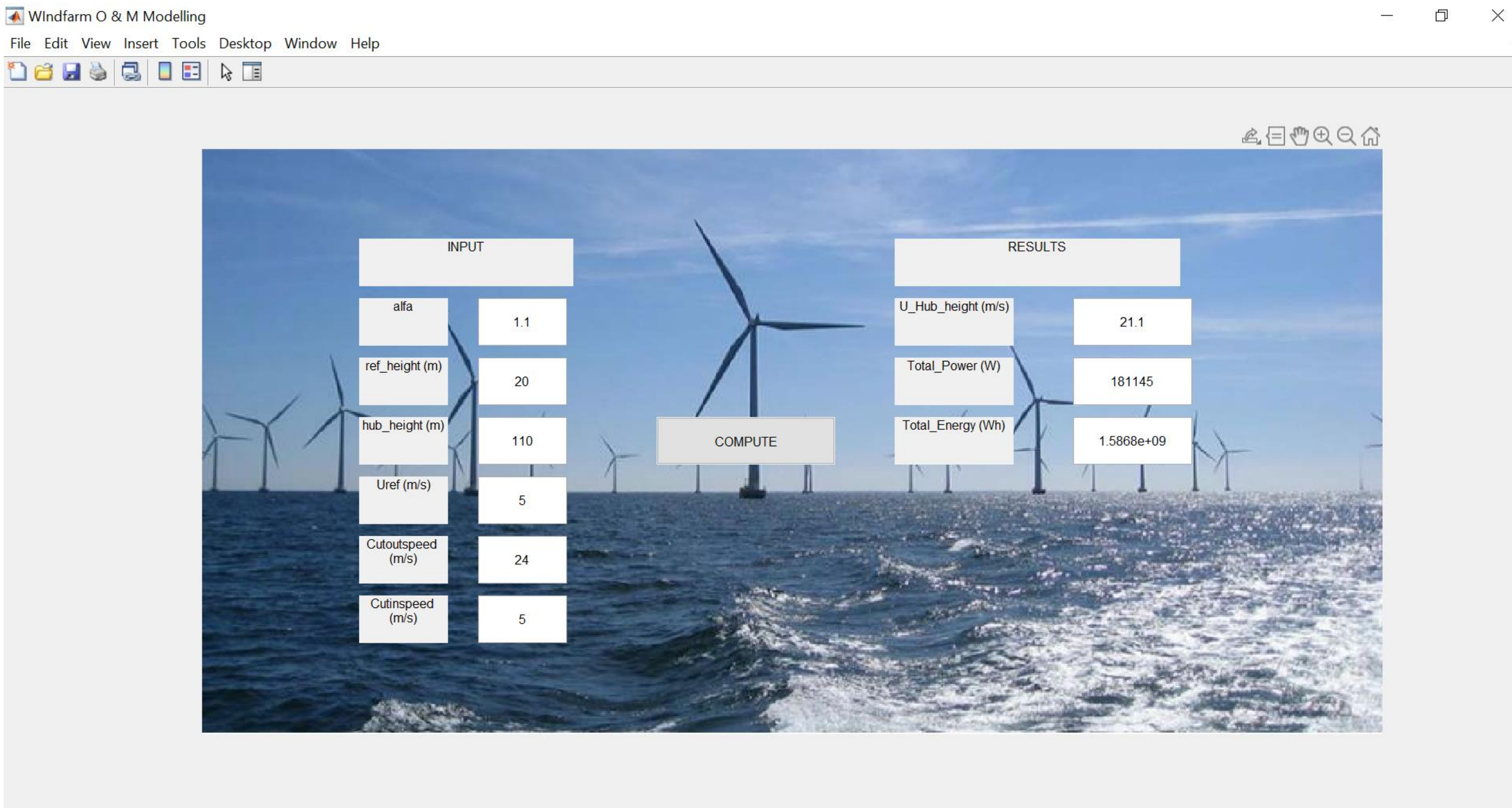
Lite version of the tool



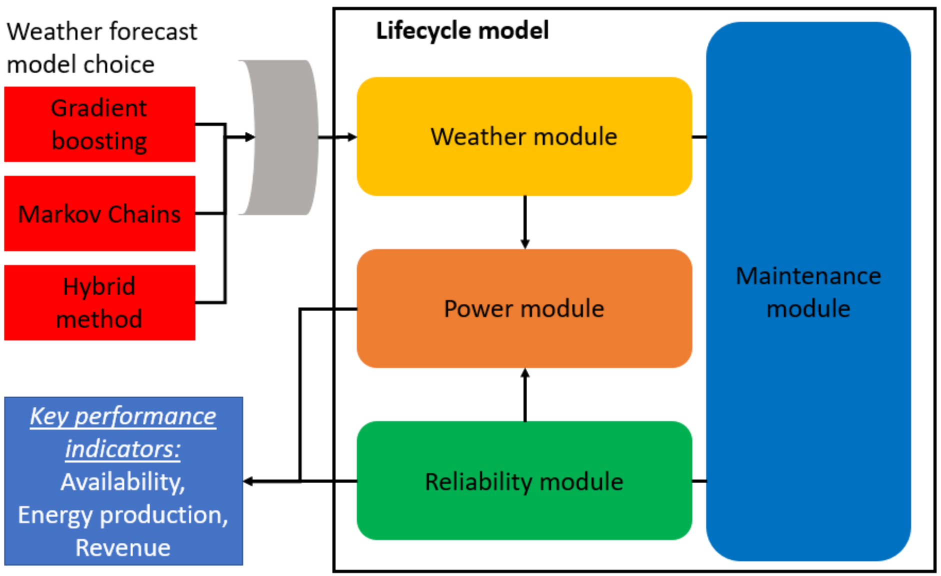


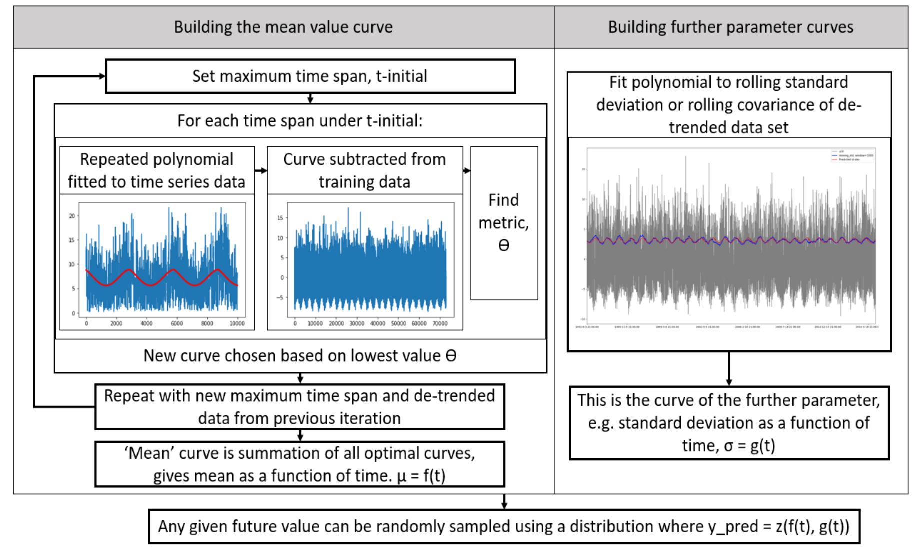
O & M Modelling Outputs – Preliminary Results



Power Module – GUI (Graphical User Interface)

Effect of weather forecast uncertainty to offshore wind farm availability assessment

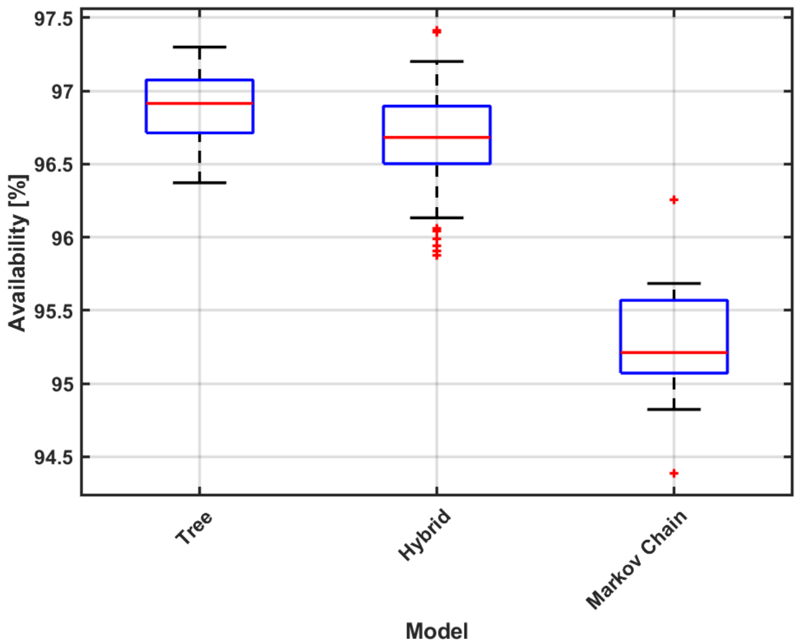


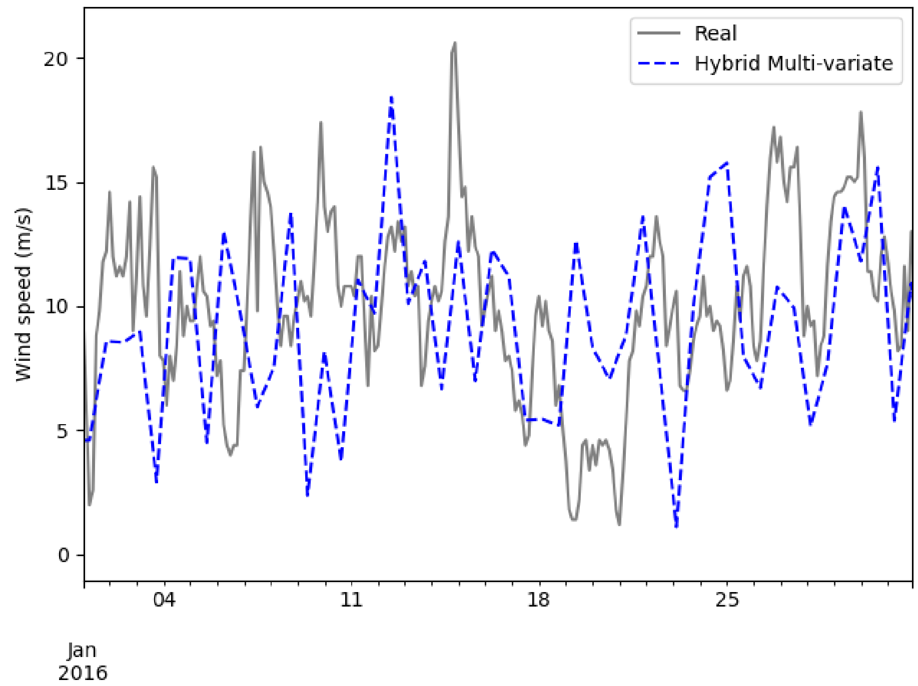


Effect of weather forecast uncertainty to offshore wind farm availability assessment

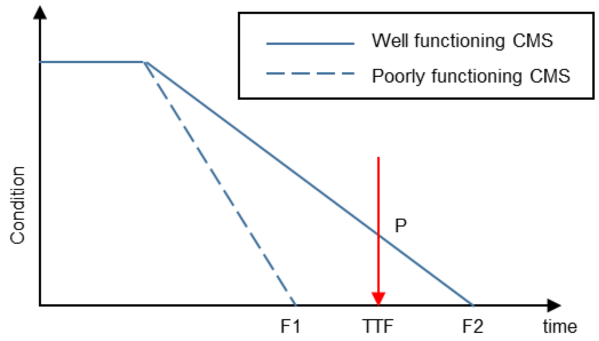
M. Richmond[1], R. Pandit[1], S. Koukoura[1], A. Kolios[1], Submitted

Effect of weather forecast uncertainty to offshore wind farm availability assessment





Influence of extended P-F intervals through condition monitoring systems on offshore wind turbine availability



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Influence of extended potential-to-functional failure intervals through condition monitoring systems on offshore wind turbine availability

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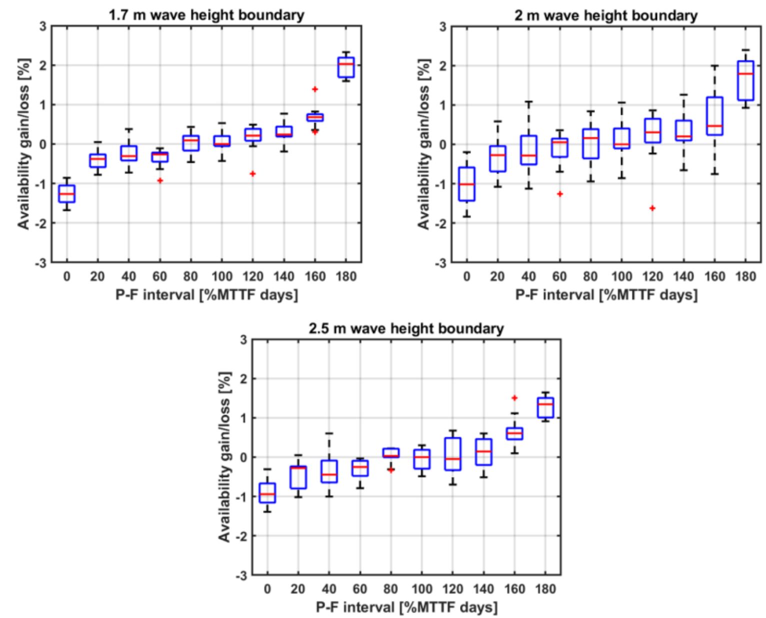

Availability gains through extended P-F intervals at different wave height boundaries of JUVs

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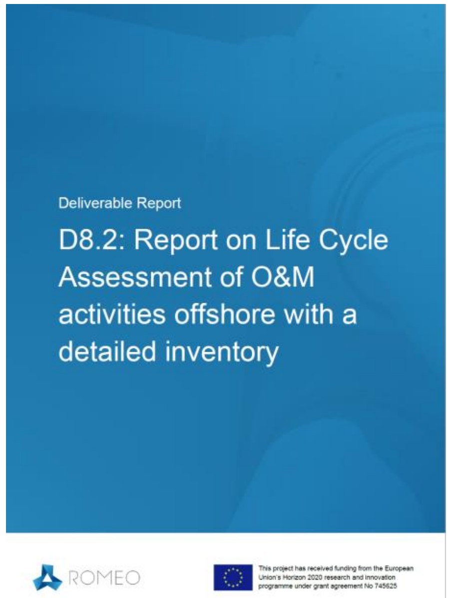
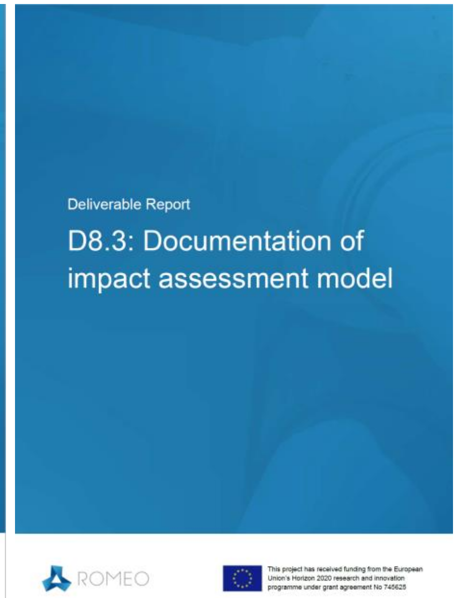
Develirables





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For further details on WP8, please contact Prof Athanasios Kolios at Athanasios.Kolios@strath.ac.uk

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