Simulation of wind power plants

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What?

- **Time domain simulation of a wind farm as a power station**
- **Capability to represent:**
  - All external environmental conditions across the site: wind, wave, current, etc.
  - Flow within the wind farm array accounting for atmospheric and wake effects
  - Performance, loading and control of each individual turbine + support structure
  - Electrical interactions between turbines and with the grid
  - Control of the wind power station as a whole

Why?

- Improve wind farm design & layout
  - More detailed understanding of terrain, wake & electrical interaction effects
- Development and testing of wind farm controls
  - Minimise wake interactions (induction control, wake steering, sector management)
  - Provide grid ancillary services (curtailment, ramp rate limits, delta control, frequency response)
  - Optimise supervisory control at wind farm level (high wind shutdown / rampdown, low voltage ride-through)
- Optimisation of O&M strategies
  - Understanding conditions experienced by individual turbines
  - Planning of scheduled maintenance

How?

✗ Not one tool based on one simulation model, but:

✓ Framework or toolbox within which different models can be linked together into a simulation platform tailored to any specific problem:

- A database structure containing all the fundamental parameters relevant to the wind power station
- A set of modelling tools of different levels of sophistication for addressing problems of different complexity
- A framework containing interfaces to the database and the modelling tools
- A user interface and workflow management system

Physical components

A wind power station is a complex combination of coupled physical systems that dictate how the entire power station behaves:

- Topographical flow effects (onshore sites)
- Metocean conditions (offshore sites)
- Atmospheric stability and turbulence
- Dynamic wind turbines with individual controllers
- Turbine wake effects (affected by atmospheric turbulence)
- Wind farm electrical systems and interconnections
- Grid connection, and interaction with the external electrical network

Constraints

- Economic revenues:
  - From electricity production
  - From providing grid ancillary services
- Operational costs / loss of revenue
  - Operation and maintenance costs
  - Environmental conditions imposed on operation (e.g. noise constraints)
  - Curtailment demands imposed by network operators

Examples of typical timescales

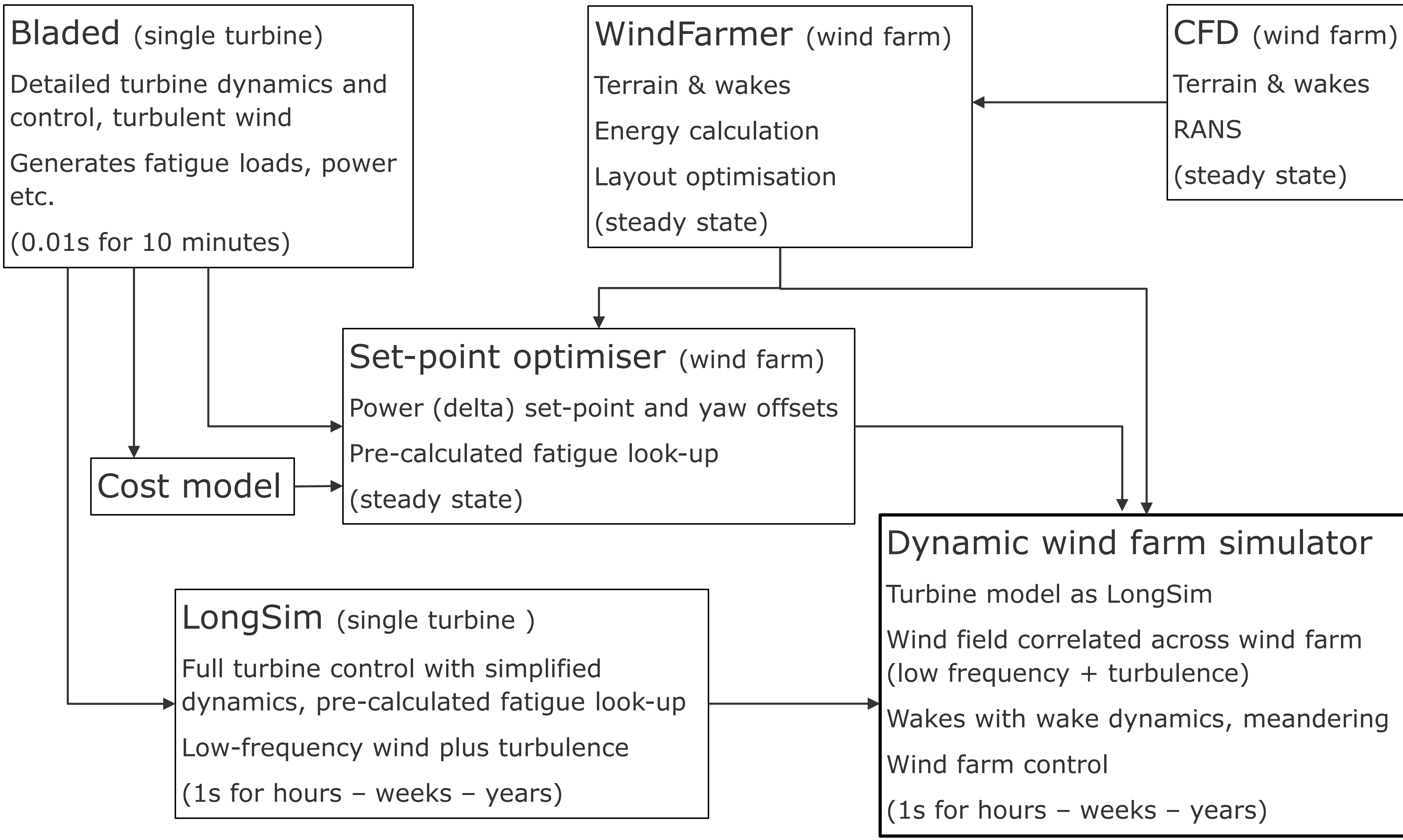
- Timesteps:
  - <1ms: electrical transients
  - ~10ms: turbine control & loads, electromechanical interactions
  - ~1 sec: turbine supervisory control and wake dynamics
  - 1-10 min: farm level control
  - 10-60 min: energy trading & forecasting
  - ~1 day: O&M planning
  - ∞ (steady-state): Farm layout design
- Length of simulations:
  - ~1s: electrical transients
  - ~1 min: grid interaction: LVRT, frequency response
  - 10-60 min: farm control for specific wind conditions, including ancillary services
  - 1hr – 1 year: supervisory control
  - 1 week – 25 years: O&M strategy

Wind field modelling

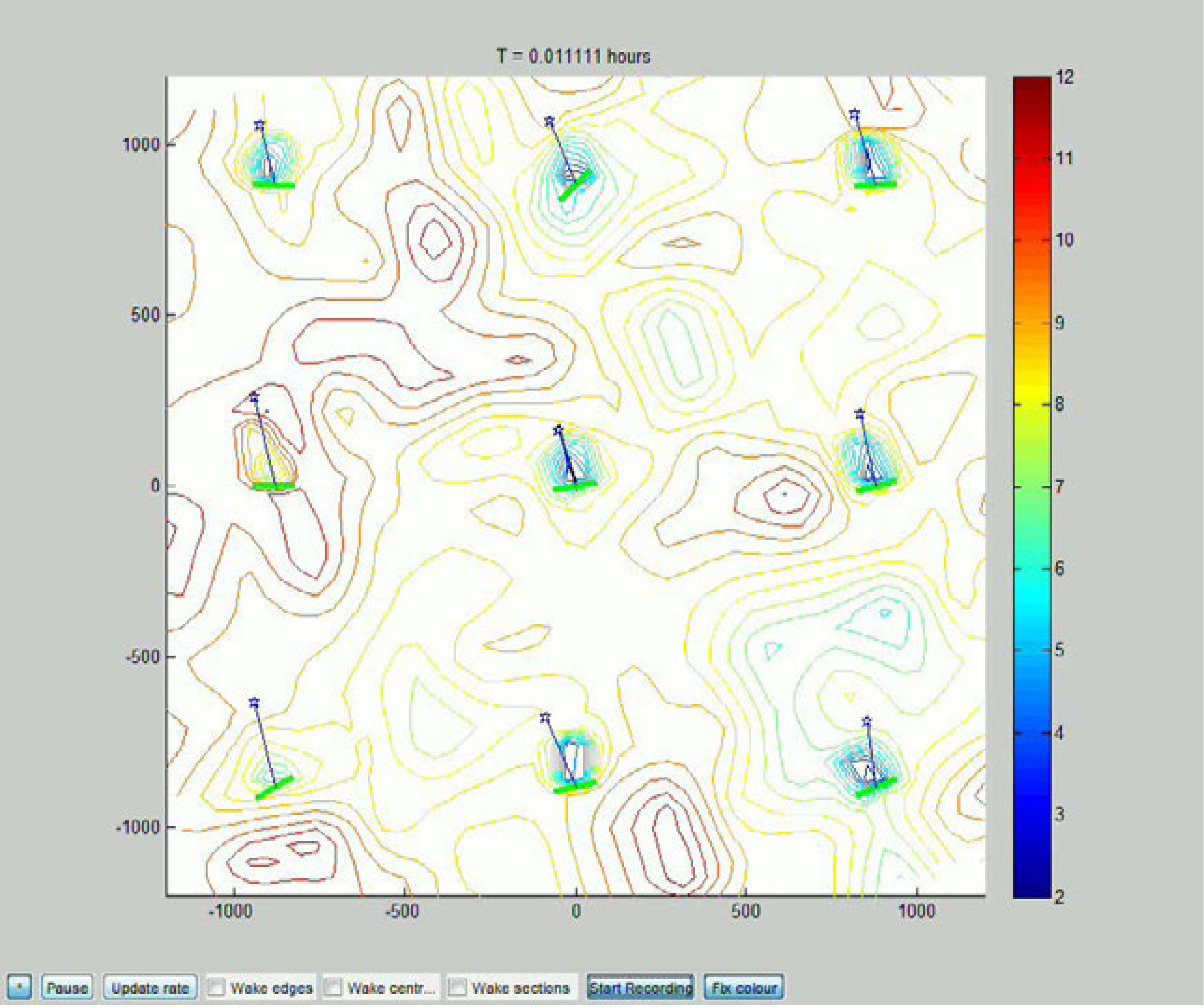
- Temporal variation:
  - Constant conditions, e.g. for simple simulations up to 10 minutes
  - Low frequency variations, e.g. for some supervisory controls, energy trading, etc.
  - Turbulence: 10-60 minute simulations with turbine & wake dynamics
  - Turbulence + low frequencies: supervisory / farm control with turbine & wake dynamics

- Spatial variation:
  - None
  - Steady-state: Terrain / topographical effects
  - Dynamic: Correlation of temporal variations across the wind farm

Pre-existing tools, further development and links



Dynamic wind farm simulator: 9-turbine example



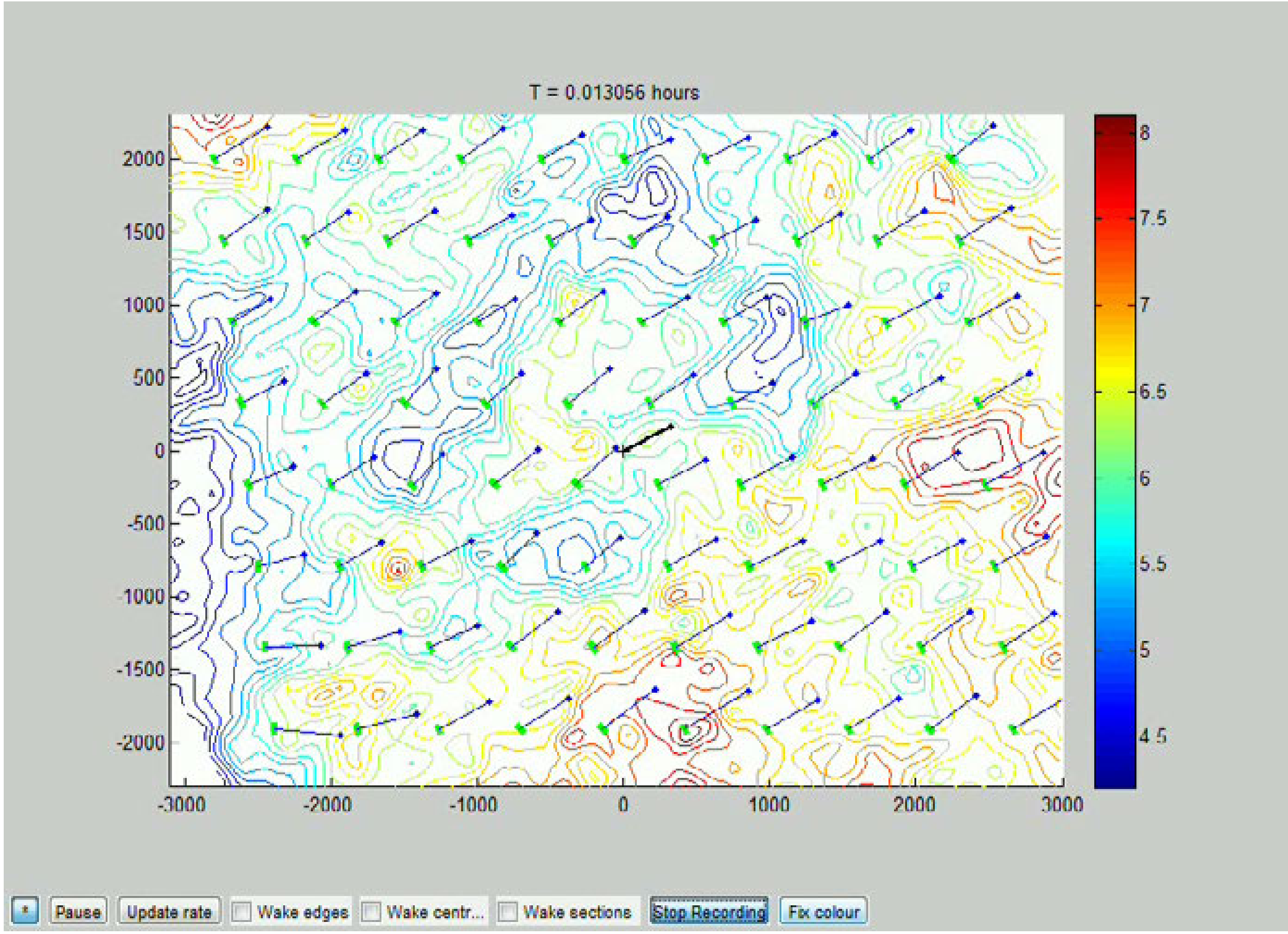
- Contour plot of wind speed
- Turbines show yaw position and local wind vector

Look out for:

- Turbulence advecting and evolving
- Wakes developing and meandering
- Wind direction changing (SSE to SSW)
- Turbine yaw control follows

One-hour simulation took 4 minutes on a lap-top (using one core)

Dynamic wind farm simulator: Horns Rev 1 (80 turbines)



- Low wind speed
- Rapid direction change - ~90º in a few minutes
- Direction change propagates through the farm at mean wind speed
- Faster than real time running on a single core

Toolbox vision – other interconnections

- More direct integration
  - CFD for higher-fidelity terrain & wake flow calculations
  - Site layout optimisation
  - Turbine aeroelastic model (Bladed)
  - Cost models
- Other components
  - Electrical models such as DigSILENT, PSCAD etc.
  - Grid operational models (e.g. KERMIT)
  - O&M planning models
  - Market models
  - Forecasting
  - Etc.

Example application: control of wind farm wakes

- Reduced power!
- increased loading!

Switch this turbine off?

Or reduce the power set-point of this one?

Or maybe yaw the turbine slightly to steer its wake away from the next turbine?

1. What is the optimum* distribution of power and yaw set-points for all the turbines, in this wind condition?
2. How can we maintain optimum* performance in dynamically changing circumstances?

* Optimum has to be defined – depends on energy and loading

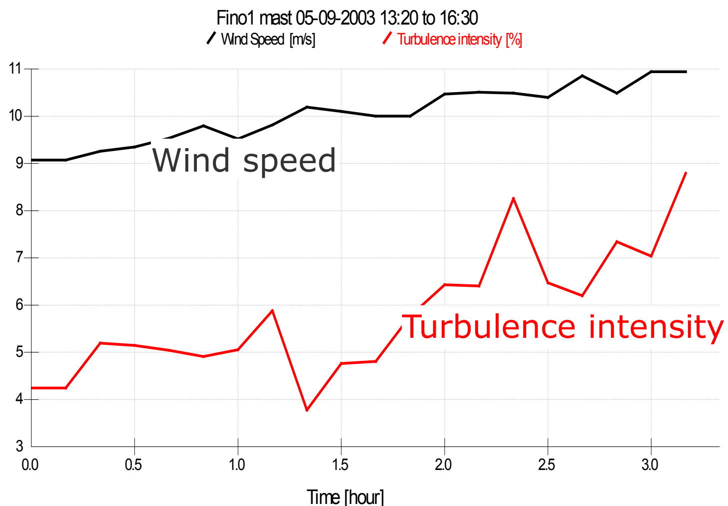
Control of wind farm wakes: Process

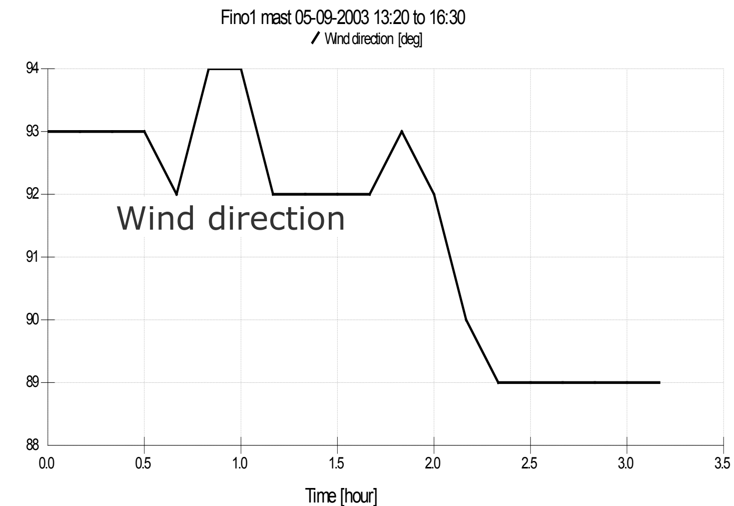
- Bladed: pre-calculate performance and fatigue loads
- Cost model: Define cost function for optimisation
- Steady-state optimiser: calculate set-points
- Dynamic wind farm simulator: simulate performance with realistically changing dynamic conditions

Example results

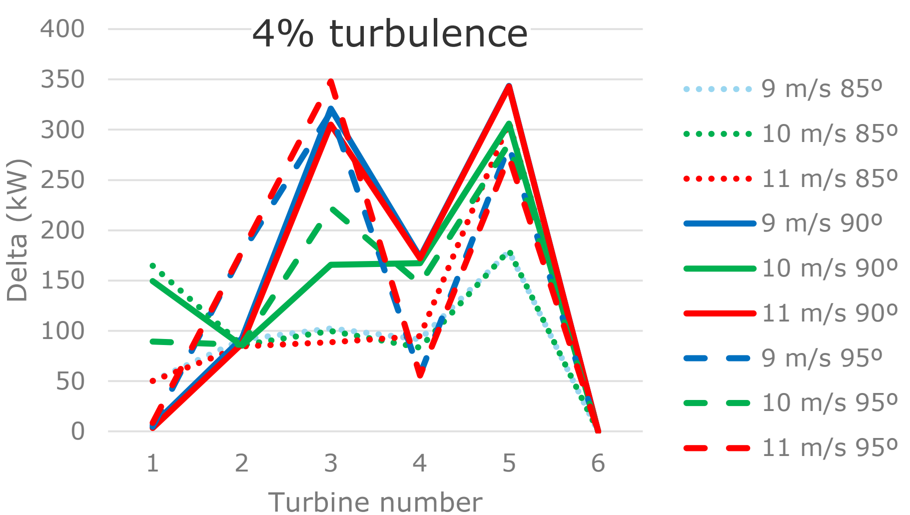
Row of 6 turbines, 3-hour simulation with changing wind conditions

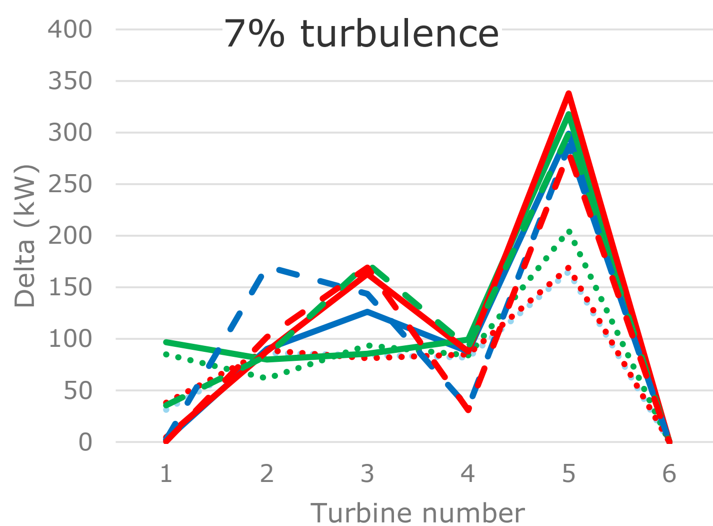
FINO-1 data:



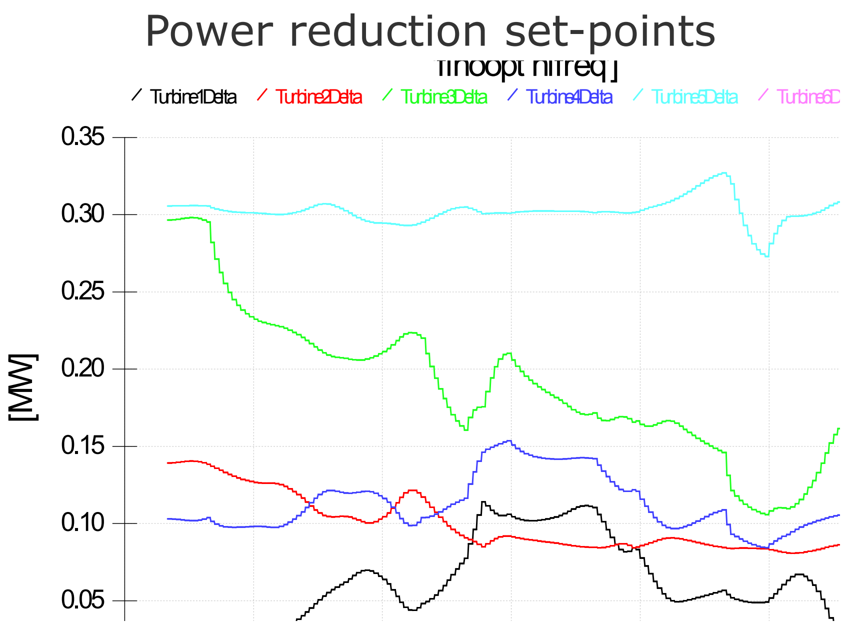


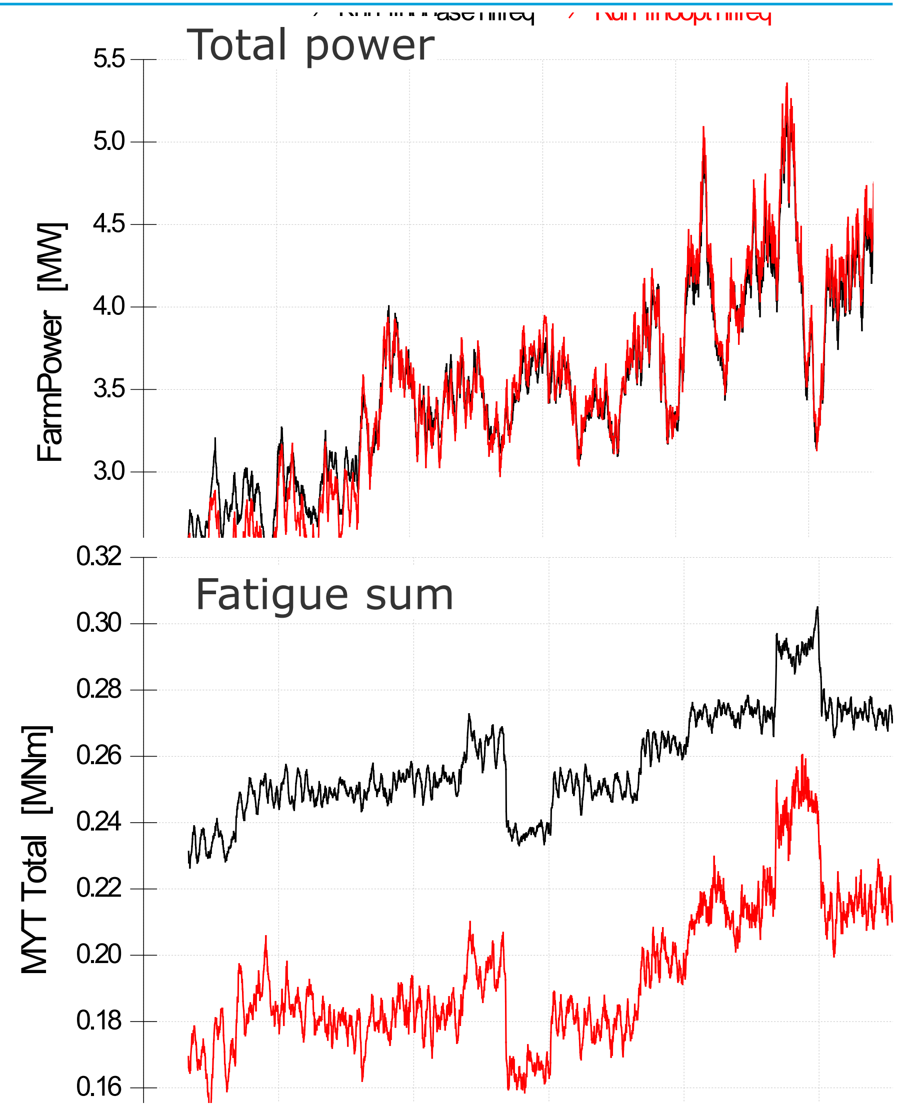
Optimal set-point matrix calculated for turbulence levels 4%, 7%, 10%





Example results: simulation output





- Set-points change with wind conditions
- Large reduction in fatigue loading
- Slight increase in energy production

Conclusions

- A basic (usable) toolset has been created, by extending several existing codes, and linking them (in ad-hoc fashion, so far…)
- Many components already validated up to a point, but more detailed validation is needed (interaction of sub-models, wider range of conditions, etc.). This will undoubtedly lead to improved or better-calibrated sub-models
- Improved or alternative sub-models can be easily plugged in as they become available
- Integration framework does not yet exist formally, and some components have not yet been linked at all (e.g. grid model)

Next steps

- Validation → improvement of sub-models
- Further component integration and software structure design

Thank you

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